Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

Philip S. Miller, Ph.D.
Senior Program Officer
IUCN SSC Conservation Planning Specialist Group

In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

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1. Valdez, R.A. 2018. Data Assimilation for the Colorado Pikeminnow Population Viability Analysis. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Data Assimilation for the Colorado Pikeminnow Population Viability Analysis

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Prepared by:

The Colorado Pikeminnow PVA Technical Team

In coordination with

Upper Colorado River Endangered Fish Recovery Program,
San Juan River Basin Recovery Implementation Program, and
Conservation Planning Specialist Group

Final Report
June 15, 2018

Preface

A Population Viability Analysis (PVA) was conducted for the Colorado Pikeminnow (*Ptychocheilus lucius*) during 2015–2018, at the request of the U.S. Fish and Wildlife Service (USFWS) in coordination with the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program. The purpose of the PVA was to evaluate the short and long-term viability of the Colorado Pikeminnow, and to provide the USFWS with information that will assist in revising the recovery criteria of the Colorado Pikeminnow Recovery Plan. The PVA was developed and conducted by Dr. Philip S. Miller of the Conservation Planning Specialist Group (CPSG) using the *Vortex* Population Viability Analysis software (Version 10) (http://www.cbsg.org/our-approach/science-based-tools/vortex).

This document provides an administrative record of the data and information assimilated for the PVA. It is the best scientific data available and was assimilated on an ongoing basis throughout the PVA process. This document is not intended to be an exhaustive treatise of the life history and demography of the Colorado Pikeminnow; rather, it is an assimilation of the more contemporary data and information pertinent to the PVA. Additional and more comprehensive information on the species can be found at the web sites of the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program: http://www.coloradoriverrecovery.org/ and http://www.fws.gov/southwest/sjrip/.

The data in this document are organized by each of the three subbasins occupied by the Colorado Pikeminnow (i.e., Green River, Upper Colorado River, and San Juan River) so that an analysis of extinction risk can be performed individually for each subbasin and for the three subbasins combined. The data are formatted consistent with PVA data needs and model structures. Where available, data were extracted from reports or publications and imported directly into the PVA stock assessment models. In other cases, data from reports were analyzed to derive parameters suitable for the models. For some parameters, data were not available for direct import or for reanalysis, and additional data assimilation and analysis were done in coordination with involved scientists.

This document was reviewed by species experts who were members of the PVA Technical Team. These experts also contributed additional information and ensured that the data were contemporary, accurate, and appropriate for the PVA. The species experts participated in the PVA process and assisted in populating the PVA models with the proper data.

Acknowledgements

Much of the information contained in this document was assimilated and provided by members of the PVA Technical Team. The Team consisted of U.S. Fish and Wildlife Service (USFWS) agency leads that included the directors and coordinators of the Upper Colorado River Endangered Fish Recovery Program and the San Juan River Basin Recovery Implementation Program; the principal investigator and PVA modeler; four species experts; and advisors from the USFWS and private entities. Members of the PVA Technical Team collectively served as the principal technical experts on various aspects of the Colorado Pikeminnow life history in the Green, Upper Colorado, and San Juan rivers. Specific contributions from members of the Technical Team are cited in the body of this report.

The following are the members of the Colorado Pikeminnow PVA Technical Team:

Name	Affiliation
Agency Leads:	
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Principal Investigator:	
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Introduction

The Colorado Pikeminnow is listed as "endangered" throughout its historic range in the states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming, as well as in Mexico (List of Endangered and Threatened Wildlife and Plants, 50 CFR 17.11 & 17.12). The species receives protection under the provisions of the Endangered Species Act of 1973, as amended (ESA; 16 U.S.C. 1531 *et seq.*), and was also designated as a "nonessential experimental population" in 1985 in the Salt and Verde rivers, Arizona (50 FR 30194), under Section 10(j) of the ESA.

Critical habitat was designated as 1,848 km of the Colorado River System on March 21, 1994 (59 FR 13374). A recovery plan for the Colorado Pikeminnow was approved March 16, 1978, and revised August 6, 1991. Recovery goals that amended and supplemented the 1991 plan were approved August 1, 2002.

A Revised Colorado Pikeminnow Recovery Plan was drafted November 25, 2014, and reviewed by stakeholders of the Upper Colorado River Endangered Fish Recovery Program (UCRRP) and the San Juan River Basin Recovery Implementation Program (SJRIP). Following the review and webinars in April and May, 2015, stakeholders and the U.S. Fish and Wildlife Service (USFWS) agreed that the downlisting and delisting criteria of the revised plan should be more clearly linked to species viability. The parties agreed that a Population Viability Analysis (PVA) could be used to help assess the current status and viability of the Colorado Pikeminnow, and to develop objective, measureable recovery criteria.

The purpose of the PVA process is to provide the USFWS with information that will assist in revising the Colorado Pikeminnow Recovery Plan. The USFWS has worked with the Colorado Pikeminnow Recovery Team since November 2012 to incorporate new information into the Revised Recovery Plan of 2014. The draft plan proposed to use a PVA to help assess species' extinction risk and as a tool for the USFWS, program managers, and species experts to reach decisions on species classification. In order for a decision on classification to be reached, a robust, peer-reviewed PVA must be developed and conducted. The Program Director's Offices (PDOs) for the UCRRP and the SJRIP proposed to complete this PVA process by building on the existing PVA developed recently for the San Juan River (Miller 2014).

The results of the PVA will be used by the USFWS to evaluate near-term risk of extinction and to refine the downlisting criteria. The PVA will also be used to develop delisting criteria (i.e., threats and demographics-based criteria that avoid long-term risk of extinction). If the PVA supports viable persistent populations, the Service could begin a rule-making process for reclassification.

This document provides a record of the data and information assimilated for the PVA. It is organized as 14 sections that correspond to species life history and demographics information. A data matrix is provided at the beginning of the document to provide a searchable summary of the data and supporting information used in the PVA.

Data Matrix

The following Table 1 is a matrix of the data and information assimilated for the Colorado Pikeminnow PVA. The data and information are organized by various parameters that characterize the species for each of the three occupied river subbasins; i.e., Green River Subbasin, Upper Colorado River Subbasin, and San Juan River Subbasin. The table contains hyperlinks that provide direct access to supporting documentation contained in the various sections of this document.

Table 1. Parameter values for Colorado Pikeminnow Population Viability Analysis. **Note that the Parameter headings 1 through 18 are hyperlinked to sections in the document that provide supporting documentation and can be accessed by pressing "Ctrl+Click" to follow the link. Note also that the section headings are hyperlinked to return to the Data Matrix.**

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
1. Distribution and Critical Habitat			
Range (Fig. 1)	• 1,278 km (798 mi) of the Green River subbasin, including the Green River and its tributaries (Yampa, White, Duchesne, Price, and Little Snake rivers) from Lodore Canyon, CO downstream to the confluence of the Colorado River.	• 476 km (296 mi) of the Upper Colorado River subbasin, including the Colorado River and its tributaries (Gunnison and Dolores rivers) from Palisade, CO downstream to the Lake Powell inflow.	• 347 km (217 mi) of the San Juan River subbasin, including the San Juan River and its tributaries (Animas River, McElmo and Yellow Jacket creeks) from Farmington, NM downstream to Lake Powell, UT.
Critical Habitat (Fig. 1)	• 984 km (614 mi) of Green River subbasin.	• 574 km (358 mi) of Upper Colorado River subbasin.	• 290 km (180 mi) of San Juan River from State Route 371 Bridge at Farmington to Neskahi Canyon in the San Juan arm of Lake Powell.
2. Population Size			
Population Size by Subbasin	• For 2000-2013, low of 1,787 adults (≥ 450 mm TL in 2012 to high of 4,206 adults in 2000, with overall average for the 10 estimates of 2,859 adults, or about 5.0 fish/mi (Table 2). • Estimates by reach and for the subbasin were computed for 1991-1999 from a	• For 1992-2015, low of 440 adults (≥ 450 TL) in 1992 to high of 897 in 2005, with overall average for the 15 estimates of 596 adults, or about 3.3 fish/mi. • Sum of concurrent estimates for Green River and Upper Colorado River subbasins was 4,979 adults in 2000;	• Only 17 wild adults were captured in the entire San Juan River between 1991 and 1995, and it was surmised that there were probably fewer than 40 adults in the entire San Juan River as of October 1995.

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	relationship of CPUE to abundance (Table 3).	3,792 adults in 2003; 3,724 adults in 2008; and 2,460 in 2013 (Table 2, Fig. 2).	• Numbers of wild fish from 1996 to 2001 was down to probably fewer than 20. • A total of 3,972,886 age-0 fish were stocked in 2002-2013, and 40,116 age-1 fish were stocked in 2003-2011 (see Section 11. Stocking). • Abundance estimates are available for <200, 200-299, 300-399, and 400-449, and =>450 mm TL (Fig. 3). • Abundance estimates are available for fish >150 mm TL in lower San Juan River (Table 4, Fig. 4).
3. Intrinsic Rate of Population Change (Lambda)			
Intrinsic Rate of Population Change (Lambda) by Subbasin	• 1991-2013: λ = 0.978. • 1991-2000: λ = 1.036. • 2000-2013: λ = 0.945 (Fig. 5). • See also Fig. 6 for annual lambda for 2000 to 2003 ISMP data.	• 1992-2015: λ = 0.985 • 1992-2005: λ = 1.025 • 2005-2015; λ = 0.927 (Fig. 7).	• The majority of Colorado Pikeminnow in the San Juan are the result of hatchery augmentation efforts. Natural reproduction is currently low and it is not reasonable to assume that there is much natural recruitment occurring.
4. Carrying Capacity (K)			
Carrying Capacity (K) by Subbasin	• Highest estimate = 4,206 adults (7.4/m); predator biomass on top of Pikeminnow biomass shows the system is not at capacity (Table 6).	• K = 897 adults (5.0/mi)—computed for reaches (Table 6).	• K = 406 adults (2.3/mi)—bioenergetic model (Fig. 8, Table 5).
5. Age and Growth			
5.1 Maximum Size and Age	• Present: ~1 m, 12 kg; mean L_∞ = 1,028 mm TL. • Growth-rate data indicate that large fish (e.g., > 900 mm TL) average 47–55 years old with a minimum age of 34 years.	• Present: ~1 m, 12 kg; L_∞ = 865 mm TL.	• Fish in SJR grow faster at earlier age, but may not reach maximum size of other populations; SJR L_∞ = 794 mm TL; GR mean L_∞ = 1,028 mm TL; UCR L_∞ = 865 mm TL.

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
5.2 Age and Size at Maturity	• All fish age 7+ (454 mm TL) were sexually mature. • All fish longer than 503 mm TL were sexually mature, and fish less than 428 mm TL were immature; 76% of 34 fish examined between 428 and 503 mm TL were sexually mature. • Hatchery-reared fish were sexually mature at age 5 (males) and age 6 (females) at total lengths of 317–376 mm and 425–441 mm, respectively.	• All fish examined were sexually mature at age 7 or 450 mm TL. Wild males spawned as early as 6 years with most at 8 years; most females did not spawn until age 9 and more likely 10 years of age.	• Stocked Colorado Pikeminnow in the San Juan River are achieving "adult" size and are able to spawn much earlier than wild-produced fish in other rivers. Adult-sized fish have been collected as early as age-4 and males less than 450 mm TL that were freely expressing milt. This is due to the much larger sizes at which they are stocked in the fall of their age-0 year (Fig. 10).
Age and Growth Relationships	• 1978-1990: L_∞ = 1152, K = 0.06293, t_o = 0.58136 (Fig. 9, Table 7).	• 1991-2005: L_∞ = 865, K = 0.0666, t_o = -0.0137 (Fig. 9, Table 7).	• 1997-2012: L_∞ = 794, K = 0.175, t_o = -- 0.255 (Fig. 9, Table 7).
5.3 Growth Rates	• Larvae at hatching are 6.0–7.5 mm long (Hamman 1981) and average about 40 mm TL (range, 29–47 mm) in October at about 3 months of age. • Growth under laboratory conditions averaged about 13 mm/30 days. • Growth of adults in the Green River was about 10.2 mm/year. • Preliminary evidence indicates that females grow larger and perhaps live longer than males. • Baseline growth rates for young fish adjusted for water temperature: $GR_{daily} = GR_{baseline} [(-0.279 + 0.0387T - 0.000637T^2) / 0.283]$; baseline growth rates were 0.41 mm/d TL for fish in the middle Green River in 1991 and 0.43 mm/d in 1992, and daily growth rates in the lower Green River were 0.44 mm/d	• Mean annual growth rate of fish from the Upper Colorado River aged 3–6 years ranged from 32.2 (age 6) to 82.0 (age 3) mm/year and declined to 19.8 mm/year for fish 500–549 mm TL; fish ≥ 550 mm TL grew an average of 9.5 mm/year.	• Growth rate is slightly higher for San Juan River than for Green or Upper Colorado rivers, possibly because fish are stocked in SJR (Fig. 10).

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	in 1991 and 0.31 mm/d in 1992 (Fig. 11). • Larvae that arrived midseason in backwaters encountered the best conditions for survival because temperatures were warm and predators were relatively small; larvae experienced up to 30 d of rapid growth to sizes that were not susceptible to predation; later-hatching larvae encountered smaller predators but experienced slower growth because of declining water temperature (Fig. 11). • Within given cohorts, mean growth rates of summer juveniles were lower than mean growth rates of autumn juveniles (Fig. 12); suggesting that CPM surviving to autumn represented fastest growing subset of summer juveniles. • In simulations of Red Shiner predation, water temperature had a large and positive effect on mean growth rate of larvae; 0.2 to 0.6 mm/d TL reflected range found for wild age-0 fish (0.15–0.65-mm/d TL) (Fig. 13). See also Fig. 27 in Predation and Competition.		
5.4 Effect of Temperature and Predator Density on Growth	• Effects of temperature and predator density on growth are shown in Fig. 11-13.	• No information available.	• No information available.
5.5 Generation Time, GT = age_{sSM} + (1/d)	• GT = 8 + [1/(1-0.80)] = 8 + 5 = 13 years.		

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
6. Length and Weight			
6.1 Maximum Size	• Historical: 1.8 m, 36 kg.		
6.2 Length-Weight Relationships (Fig. 14-15)	• Green River: $Log_{10}W$ = -5.692 + 3.206 * $Log_{10}L$. • During population increase (1991-1999): Log_eW = -12:365 + 3:105 * Log_e (TL). • During population decline (2000-2003): Log_eW = -12:20 + 3:068 * Log_e (TL).	• Upper Colorado River: $Log_{10}W$ = -6.384 + 3.463 * Log_{10} L. • April 1990-94: $Log_{10}W$ = -5.548 + 3.173 * Log_{10} (TL). • May 1990-94: $Log_{10}W$ = -5.773 + 3.260 * Log_{10} (TL). • June 1990-94: $Log_{10}W$ = -5.603 + 3.207 * Log_{10} (TL).	• Jan-May: $Log_{10}W$ = -5.1707 + 3.0005 * Log_{10} L. • June-Sept: $Log_{10}W$ = -5.2666 + 3.0405 * Log_{10} L.
7. Fecundity, Hatching, and Temperature			
7.1 Fecundity (eggs/female)	• Fecundity relationships are exponential and not well described by simple relationships of eggs/kg of adult. A larger fish is likely to produce more eggs per unit weight than a smaller one. This will or should matter for populations with different size structures. • For average fish size of 681 mm TL, average 11,000 eggs/fish or 3,895 eggs/kg (Table 8). • For 10 injected hatchery-reared females, 78,540 eggs for an average of 10,542 eggs/kg (Table 8). • Average of injected hatchery-reared 9-year old females (n = 24) was 77,400 eggs (range, 57,766–113,341) or 55,533 eggs/kg, and average of 10-year old females (n = 9) was 66,185 eggs (range, 11,977–91,040) or 45,451 eggs/kg (Table 9).		• No estimates of fecundity specific to San Juan River (assumed to be the same as for Green River and Upper Colorado River populations).
7.2 Temperature Requirements	• Spawning activity documented after the peak of spring runoff during June–August at water temperatures of 16°C or higher. • Average hatch in constant and fluctuating temperatures was 72% at 18°C, 67% at 22°C, 62% at 26°C, and 38% (constant temperature only) at 30°C. There was no significant difference in hatch between constant	• In a laboratory setting, hatching success was greatest at 20–24°C with incubation time of 90–121 h. • Eggs in the wild incubate in gravels for about 5 days. Newly hatched larvae are 6.0–7.5 mm long, which emerge from spawning cobbles several days after hatching and drift predominantly as protolarvae.	• Mean water temperature during the back-calculated spawning dates of drifting larval Pikeminnow (8 July to 18 July) ranged between 18.0°C and 18.5°C and had risen about 5°C several weeks before spawning. • Annual thermal units at locations of the San Juan River before and after construction of Navajo Dam are provided (Fig. 16).

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	and fluctuating temperatures, Average survival of larvae to 7 d post-hatch in constant and fluctuating temperatures was 68% at 18°C, 64% at 22°C, 83% at 26°C, and 13% (constant temperature only) at 30°C. • Hatch was highest at l8°C (regimes combined) and lowest at 26°C, but survival to 7 d post-hatch was lowest at l 8°C and highest at 26°C. If overall reproductive output (product of % hatch and % survival of larvae) to 7 d is considered the "optimum temperature" for reproduction by Colorado squawfish may be 18-26°C. The lower temperature limit for incubation is unknown but survival was < 3% among embryos incubated at l 2-l 3°C. The upper temperature limit for incubation is probably near 30°C. • Dates of hatching are shown for different reaches of the Green River (Fig. 17). • Incubation times based on field studies of drift captured larvae that were aged. • In the lower Yampa River, reproduction was initiated within days of mean daily water temperature exceeding 18°C, with water temperature at initiation ranging 16.0–22.3°C on the Yampa River and 19.8–23.0°C on the lower Green River.		

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
7.3 Sex Ratio	• 9:1 (M:F). • 13.85:1. • 5.6:1. • Hatchery conditions: 2–3:1.	• 4.5:1 (M:F). • 3:1. • 1.11:1 from field examination—used as standard by USFWS (2014). • Males typically show up sooner and stay longer on spawning areas where large numbers are easily captured which may bias ratios toward a large number of males.	• No assessment of sex ratio for San Juan River; need more time for hatchery fish to reproduce and for sex ratio to become established.
8. Movement and Transition			
8.1 Movement (Fig. 18)	• The Colorado Pikeminnow is a long-distance migratory species, classified as “potadromous” or migratory within the river basin. Average movement of 31.8 km was observed for 43 radio-tagged adults during fall and spring in the Green River. Adults remain in home ranges during fall, winter, and spring and may move considerable distances to and from spawning areas in summer. Individuals move to spawning areas shortly after runoff in early summer, and return to home ranges in August and September. Round-trip movements of up to 950 km have been reported, with some fish “straying” between rivers within the Green River subbasin. Adults may return in consecutive years to overwinter in the same areas.	• In the Upper Colorado River, distance moved was inversely related to fish size; displacement of fish < 550 mm TL averaged 33.6 km and displacement for fish ≥ 550 mm TL was only 7.5 km.	•
8.2 Exchange among Subbasins	• Annual transition probabilities are available for 2000-2003 in Table 10; transition rates are length dependent,	• Annual transition probabilities are available for 1991-2005 in Table 11; transition rates are length dependent,	• No documented exchange of Colorado Pikeminnow between the San Juan River and either the Green River or the Upper

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	with younger and smaller fish moving more than older larger ones. • 1991-2010: Of 2,203 fish initially tagged in the Green River system and recaptured at least once, 1.0% were recaptured in the Colorado River system; 1 fish returned, hence, 1.0% of Green-River-tagged fish emigrated to the Colorado River system (Table 12).	with younger and smaller fish moving more than older larger ones. • 1990-2010: Of 773 fish initially tagged in the Colorado River system and recaptured at least once, 3.4% were recaptured in the Green River system; 5 fish returned, hence, 2.7% of Colorado-River-tagged fish emigrated to the Green River system (Table 12).	Colorado River, although many Colorado Pikeminnow are found in the SJR inflow to Lake Powell.
9. Larval Drift and Transport			
9.1 Larval Drift and Transport	• Numbers of larvae in drift nets by year is provided for the lower Yampa and lower Green rivers for 1990-2012 (Fig. 19). • Numbers of larvae in drift nets by year is provided for the lower Yampa River for 1990-2013 (Fig. 20).	• Larval drift data not found (data may be available from Rick Anderson).	• 6 larvae were caught in drift nets, 1991-1997. • 40 larvae were caught with active gear, 2004 to 2011. • Altogether (all gears, all habitats), 58 larvae were captured from 1993 to 2013, and 312 were captured in 2014.
9.2 Relationship of Flow to Larval Transport	• Larval transport is provided for the lower Yampa River (Fig. 21) and for the lower Green River (Fig. 22). • Flow to age-0 relationship also in Haines and Tyus (1990)—not accessed.	•	•
10. Age-0 Density and Backwater Availability			
10.1 Age-0 Density	• Mean annual density of age-0 fish in backwaters of the middle and lower Green River is provided for 1979-2012 (Fig. 23).	•	•
10.2 Backwater Availability	• Backwater number and area per km are provided for reaches of the middle Green River, 1987 (Fig. 24), and for the	•	• Surface area of backwater habitats by year and geomorphic reach, as

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	middle and lower Green River for 1979-2012 (Fig. 25). • See also Chart and Trammell (1999) and Day.		measured during fall base flow is provided (Fig. 26).
11. Stocking			
Stocking by Subbasin	• About 32 000 fingerlings stocked in Kenney Reservoir of the White River in April 1989; unknown number stocked in 1988.	• About 1,500 age VI fish were stocked in the Colorado River near Moab, UT in April 1980. • 5,084 hatchery-reared fish were stocked in the Gunnison and Colorado rivers in 2003 and 2004 (Table 13). None of 2,069 stocked in 2003 were recaptured, and 72 of 3,015 stocked in 2004 were recaptured to 2008. Estimated survival rate of stocked fish after 4 years was 0.3%.	• Between 1996 and 2006, over 2.7 million fish were stocked (Ryden 2003b, 2004). • Between 175,928 and 475,970 age-0 fish were stocked annually in November during 2002 to 2014 (total: 4,366,328; Table 14). • Between 353 and 12,661 age-1+ fish were stocked annually in November during 2002 to 2011 (total: 40,116; Table 15). • Numbers recaptured by year are shown in Tables 14 and 15. • Estimated number of age 2+ fish (> 150 mm TL) was 4,666 in 2009 and over 5,400 in 2010.
12. Predation and Competition			
12. Predation and Competition by Subbasin	• There are no direct relationships available for effect of predation for a given species on CPM, nor for the various sizes of fish present; these processes are all length dependent, which would confound any efforts to estimate this even if we knew a rate. • Red shiner predation was significant because survival of CPM larvae was	• There are no direct relationships available for effect of predation for a given species on CPM.	

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	only 1.3–8.5% in warm thermal regime and 0.8–4.3% in cool thermal regime (Fig. 27); survival was relatively low for larvae with early or late hatching dates compared to midseason hatching dates; larvae that hatched early experienced rapid growth because backwater temperatures were relatively warm, but larger and more efficient red shiner predators reduced larval survival; larvae that arrived midseason in backwaters encountered best conditions for survival because temperatures were warm and predators were relatively small. • Similar to growth rates observed in field studies, simulated growth rates of CPM that survived to the end of the growing season shifted to fish with faster growth rates compared to initial distribution (Fig. 28); because size-selective predation by red shiners tended to remove smaller CPM with relatively low growth rates faster than fish with higher growth rates. • Numbers of Red Shiner, Fathead Minnow, and Sand Shiner captured in backwaters with Colorado Pikeminnow are shown in Fig. 29.		
13. Habitat			
13.1 River Gradients	• Spawning sites of Colorado Pikeminnow in the Green River, Upper Colorado River, and Yampa River are located in river reaches with gradients of 5.3 and 11.3, 7.7, and 8.2 ft/mi, respectively; whereas nursery areas in the Green River and Upper Colorado		• The gradients of the San Juan River from Navajo Dam to Animas River, Animas River to Bluff, and Bluff to Clay Hills are 13.2, 7.4, and 8.3 ft/mi, respectively (Fig.

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
	River occur in reaches with lower gradients of 1.6 and 3.0, and 2.3 ft/mi, respectively (Fig. 30).		30), which are within the range of gradients used for spawning, but higher than gradients used as nursery areas in other rivers.
13.2 Fish Passage	• All reaches in the Green River are accessible to fish; the only diversion dam in occupied habitat at Tusher Wash was redesigned with fish passage in 2016.	• Fish passage has been provided to all historic range in the Upper Colorado River with passage facilities at the Redlands Water and Power Company on the Gunnison River (selective fish passage completed in 1996); and the Grand Valley Irrigation Company (nonselective, 1998), Grand Valley Project (selective, 2004), and Price-Stubb (nonselective, 2008) on the Upper Colorado River.	• Three physical barriers to fish movement have been modified: Cuedi Diversion (removed, 2001), Hogback Diversion (nonselective fish passage, 2001), and Public Service Company of New Mexico Weir (selective fish passage, 2003) (Fig. 31). • Fish passage at two other mainstem barriers (i.e., Arizona Public Service Company Weir and Fruitland Diversion) are in the design phase that will allow access to an additional 288 km of critical habitat (Fig. 31).
13.3 Temperature Suitability	• Modifications to the penstocks at Flaming Gorge Dam in 1976 provided the flexibility to release a mixture of warmer water, and native fish, including Colorado Pikeminnow, have expanded upstream range in the upper Green River.	• Cold releases from the Aspinall Unit dams on the Gunnison River may restrict use and upstream range by Colorado Pikeminnow. Recent studies show that it is possible to meet downstream temperature targets in the Gunnison River through incorporation of a multiple-level selective withdrawal structure at Blue Mesa Dam that could allow for an expansion of the Colorado Pikeminnow population about 40 km upstream in the Gunnison River.	• Expanding the range of the Colorado Pikeminnow upstream of Farmington will require warming releases from Navajo Dam. One option for warming temperature of the San Juan River is to modify releases from Navajo Dam with a temperature control device (Fig. 32).
13.4 Mesohabitat Use (Tables 16-18)	• Throughout the year, juveniles, subadults, and adults use relatively deep, low-velocity eddies, pools, and runs that occur in nearshore areas of main river channels. In spring, adults use floodplains, flooded tributary mouths, flooded side canyons, and eddies that are available at high flows.		

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
13.5 Spawning Sites	• Spawning sites in the Green River subbasin have been documented in the lower Yampa River and in Gray Canyon on the lower Green River. These reaches are 42 and 72 km long, respectively, but most spawning is believed to occur at one or two short segments within the two reaches.	• Suspected spawning sites in the Upper Colorado River subbasin are at six locations in meandering, alluvial reaches, including the 15-mile reach upstream of the Gunnison River.	• Two potential spawning areas were located in "the mixer area" at RM 131 and 132 during a radiotelemetry study. • More recently, spawning-related activity has been seen in the San Juan River near the Four Corners area.
13.6 Habitat Suitability Indices	• Habitat Suitability Indices are provided in Fig. 33.		
13.7 Estimated Capacity of Backwater Habitat	• The number of larvae in backwaters of the Green and Upper Colorado rivers is provided in Fig. 35.		• Densities of larvae in backwaters are provided in Fig. 34 • Estimated capacity of larvae in backwaters is provided in Fig. 36.
14. Genetics			
14.1 Genetic Diversity	• Allele frequencies from 633 wild fish and 94 hatchery fish did not differ significantly among geographically separated breeding populations, suggesting essential panmixia across the four rivers sampled (i.e., Green, Yampa, Colorado, and San Juan; Morizot et al. 2002). • The most striking geographic variability was the presence of the rare private alleles GR*b and TPI-2*c in Green River samples and GPI-2*c, PEPB*a, and PEPS*b in Colorado River samples. The lowest genetic variability was observed in the San Juan River samples, possibly the result of prior population bottlenecks.		
14.2 Genetic Effective Population Size (N_e)	• N_e =2,500, from base N_e of 500, sex ratio of 1.11:1, and N_e/N_g of 0.20.		
15. Parasites and Diseases			
Parasites and Diseases	Principal parasites are: an external parasitic copepod (*Lernaea cyprinacea*), the protozoans *Myobolus* sp. and *Trichodina* sp., the trematode *Ornithodiplostomum* sp., the bass tapeworm (*Proteocephalus ambloplites*) found in 65% of stomachs from fish larger than 200 mm TL in the Green River (Vanicek 1967), a cestode identified as *Proteocephalus ptychocheilus*, and the Asian tapeworm (*Bothriocephalus achielognathii*).		• Parasites of Colorado Pikeminnow have not been surveyed in the San Juan River.

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
16. Diet			
Diet	• Principal food items of young up to about 50 mm TL in nursery backwaters are cladocerans, copepods, and midge larvae (Vanicek 1967; Jacobi and Jacobi 1982; Muth and Snyder 1995). • Insects became important for fish up to about 100 mm TL, after which fish are the main food item. • Vanicek (1967) reported Colorado Pikeminnow as small as 50 mm TL with fish remains in their guts, and Muth and Snyder (1995) reported fish remains in the gut of a Colorado Pikeminnow 21 mm TL. • Young in hatchery troughs may become cannibalistic at sizes of less than 50 mm TL (personal communication, F. Pfeifer, USFWS). • Adults consume primarily soft-rayed fishes, including bluehead sucker, flannelmouth sucker, red shiner, sand shiner, and fathead minnow (Osmundson 1999). • Colorado Pikeminnow have been reported with channel catfish lodged in their throat that may be a cause of death for the Pikeminnow (McAda 1980; Pimental et al. 1985).		• Diet of Colorado Pikeminnow has not been surveyed in the San Juan River.
17. Water Quality			
17a. Selenium	•	• Muscle plugs from 16 Colorado Pikeminnow captured at Walter Walker State Wildlife Area (WWSWA) contained a mean selenium concentration of 17 µ/g dry weight, which was over twice the recommended toxic threshold guideline concentration of 8 µ/g dry weight in muscle tissue for freshwater fish. • Muscle plugs were retaken in 1995 (11 were same fish). Selenium concentrations in 9 of the 11 recaptured fish were significantly lower in 1995 than in 1994. • Reduced selenium may in part be attributed to higher instream flows in	• No muscle plugs have been taken from Colorado Pikeminnow from the San Juan River. • Concentrations of selenium in water samples collected from the mainstem exhibited a general increase in maximum recorded values with distance downstream from Archuleta, New Mexico, to Bluff, Utah, (<1 microgram per liter [µg/L] to 4 µg/L). The safe level of selenium concentrations for protection of fish and wildlife in water is considered to be <2 µg/L, and chronically toxic levels are considered to be >2.7 µg/L.

Parameter	Green River Subbasin	Upper Colorado River Subbasin	San Juan River Subbasin
		1995 and lower water selenium concentrations in the Colorado River in the Grand Valley. • In 1996, muscle plugs were taken from 35 Colorado Pikeminnow from WWSWA, and no difference in mean selenium concentrations were detected from those sampled in 1995.	
17b. Mercury	• The impact of mercury (or the functional relationship of mercury and reproductive impairment) on the Colorado Pikeminnow in the San Juan River was derived for purposes of the PVA and is described in the PVA report by Miller (2014). See Figs. 37-43, Table 19.		
18. Mortality Rates			
18. Survival by Subbasin (Tables 20-24)	• Average annual survival of sub-adults and adults from the Green River subbasin was 82% during 1991–1999, 65% during 2001–2003, and 80% during 2006–2008 (Tables 20-21, Fig. 44; Bestgen et al. 2005, 2010).	• Average annual survival of adults ≥ 500 mm TL during 1991–1994 was 88.2% (95% CI = 85–91%); 85.9% (95% CI = 81–89%) during 1998–2000, and 80.4% (95% CI = 66–90%) during 2003–2005; average annual survival of adults over the three sample periods was 85% (Fig. 45; Osmundson and White 2009).	• Age-0 to Age-1: 0.014 (Durst USFWS). • Age-1 to Age-2: 0.841 (Durst USFWS). • Age-1 to Age-2: 0.467 (Durst USFWS). • Age-2 to Age-3: 0.409 (Durst USFWS). • Fig. 46, Table 22.

1.0 Distribution and Critical Habitat

Wild populations of the Colorado Pikeminnow remain in about 2,101 km (1,311 mi) of the Colorado River System in three subbasins (Figure 1).

1.1 Green River Subbasin

The Green River population is distributed in about 1,278 km (798 mi) of the Green River subbasin, including the Green River and its tributaries (Yampa, White, Duchesne, Price, and Little Snake rivers) from Lodore Canyon, CO downstream to the confluence of the Colorado River (Bestgen et al. 2010). Critical habitat in the Green River subbasin includes 984 km (614 mi) of the Green, Yampa, and White rivers.

1.2 Upper Colorado River Subbasin

The Upper Colorado River population is distributed in about 476 km (296 mi) of the Upper Colorado River subbasin, including the Colorado River and its tributaries (Gunnison and Dolores rivers) from Palisade, CO downstream to the Lake Powell inflow (Osmundson and White 2009). The species is found in the Lake Powell inflows of the Upper Colorado River and the San Juan River, but there is no known movement of Colorado Pikeminnow between these subbasins. Critical habitat in the Upper Colorado River subbasin includes 574 km (358 mi) in the Colorado and Gunnison rivers.

1.3 San Juan River Subbasin

The fish in the San Juan River are distributed in about 347 km (217 mi) of the San Juan River subbasin, including the San Juan River and its tributaries (Animas River, McElmo and Yellow Jacket creeks) from Farmington, NM downstream to the Lake Powell inflow in UT (Holden 1999). There is no known movement of Colorado Pikeminnow across Lake Powell, between the San Juan River subbasin and the Upper Colorado River subbasin. Critical habitat in the San Juan River subbasin includes 290 km (180 mi) of the San Juan River from the State Route 371 bridge at Farmington to Neskahai Canyon in the San Juan arm of Lake Powell (59 FR 13374).

1.4 Salt and Verde Rivers

During 1981–1990, over 623,000 Colorado Pikeminnow of various sizes were introduced into historical habitat in the Salt and Verde rivers, tributaries of the Gila River in Arizona, to reestablish the species in the lower basin (Hendrickson 1994). These reintroductions were part of conservation efforts, and the surviving individuals were classified as an "experimental nonessential" population in 1985 (50 FR 30194), under Section 10(j) of the ESA. Stocking of Colorado Pikeminnow into the Verde River by Arizona Game and Fish Department continues annually (Hyatt 2004), but a reproducing population has not become established (Robinson 2007). The fish of the Salt and Verde rivers were not considered in this PVA.

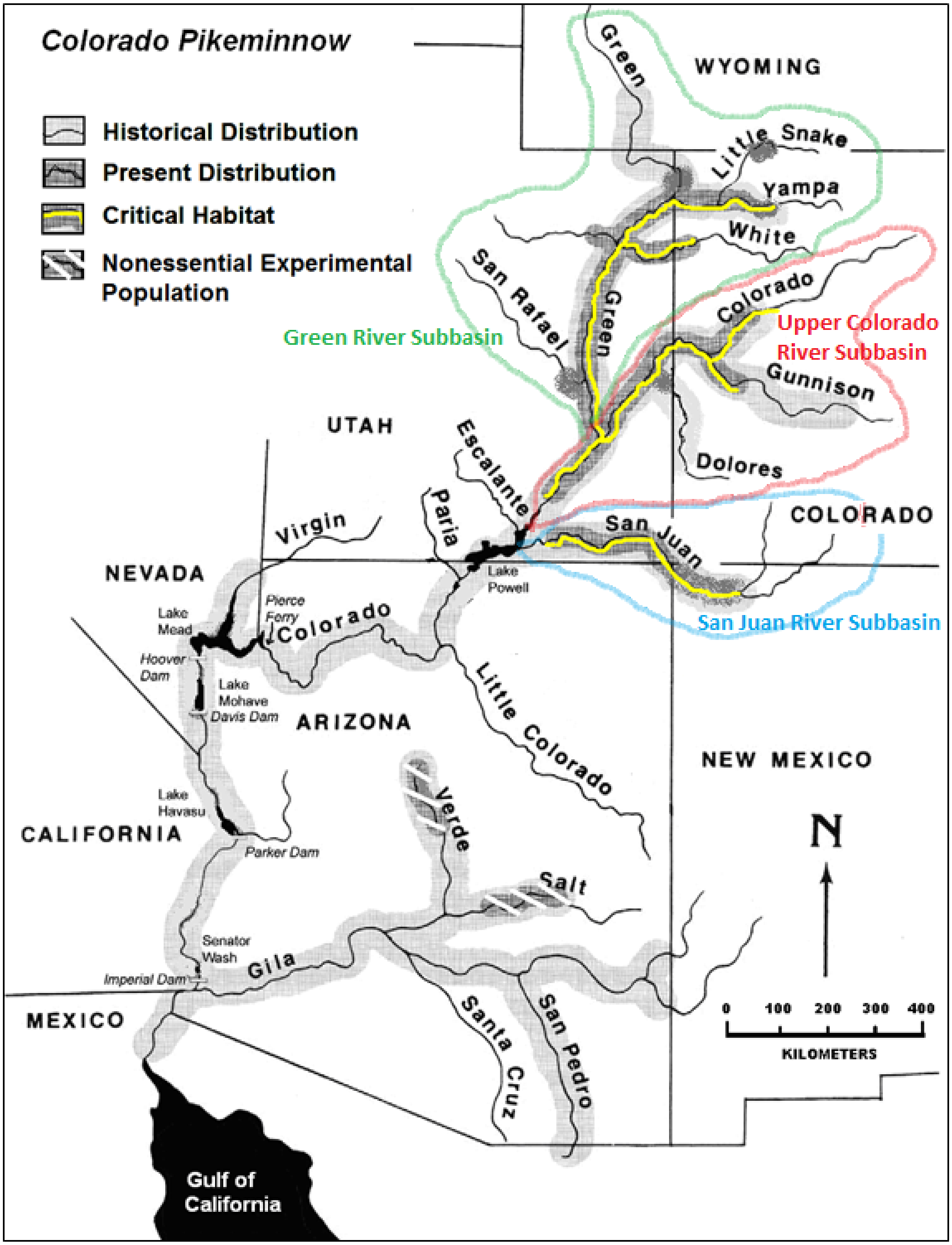

Figure 1. Distribution and critical habitat of the Colorado Pikeminnow in the Colorado River System (U.S. Fish and Wildlife Service [USFWS] 2014).

2.0 Population Size

2.1 Green River Subbasin

The Green River population ranged from a high of 4,206 adults (age 7+, ≥ 450 mm total length [TL]) in 2000 to a low of 1,787 adults in 2012 (Tables 2, Figure 2), with an overall average for the last 10 estimates (2000-2013) of 2,859 adults, or about 5.0 fish/mi (for 916 km or 569 mi of river). Estimates by reach and for the subbasin were computed for 1991-1999 from a relationship of CPUE to abundance (Table 3; Bestgen, Pers. Com. 2016).

2.2 Upper Colorado River Subbasin

The Upper Colorado River population ranged from a low of 440 adults in 1992 to a high of 897 adults in 2005 (Table 2, Figure 2), with an overall average for the 15 estimates of 596 adults, or about 3.3 fish/mi (estimates include 292 km or 181 mi of river). The sum of the more recent concurrent estimates for the Green River and Upper Colorado River subbasins was 4,979 adults in 2000; 3,792 adults in 2003; 3,685 adults in 2008; and 2,460 in 2013.

2.3 San Juan River Subbasin

The number of adult Colorado Pikeminnow in the San Juan River is small and estimates of adults are not available. Only 17 wild adults were captured in the entire San Juan River between 1991 and 1995, and it was surmised that there were probably fewer than 40 adults in the entire San Juan River as of October 1995 (Holden 1999). The numbers of wild fish from 1996 to 2001 was down to probably fewer than 20 (Ryden 2003a, 2004; SJRIP 2006). In 2009, Ryden (2010) estimated 26 adult Colorado Pikeminnow (≥ 450 mm TL) from electrofishing data using a 5% capture probability (*p*-hat).

Colorado Pikeminnow have been stocked in the San Juan River since 1996. A total of 3,972,886 age-0 fish were stocked in 2002-2013, and 40,116 age-1 fish were stocked in 2003-2011 (Durst 2015; see section 11. Stocking). River-wide abundance estimates are provided in Figure 3 for size categories >200 mm TL, and estimates of juveniles ≤ 150 mm TL for the lower river (RM 3-94) are provided in Table 4 and Figure 4 (Hines 2015).

2.4 Other Regions of the Colorado River System

Efforts to reestablish the Colorado Pikeminnow have also taken place in the Lower Colorado River Basin. Over 623,000 hatchery fish were introduced into historic habitat in the Salt and Verde rivers, tributaries of the Gila River in Arizona, during 1981–1990 (Hendrickson 1994; Figure 1). These reintroductions were part of conservation efforts and the fish were classified as a "nonessential experimental population" in 1985 (50 CFR 17.11). Colorado Pikeminnow continue to be stocked annually into the Verde River by Arizona Game and Fish Department (Hyatt 2004) where small numbers persist, but with low survival and no evidence of natural reproduction (Robinson 2007).

Table 2. Annual mark-recapture population estimates and 95% confidence intervals for adult Colorado Pikeminnow (age 7+, ≥ 450 mm TL) in the Green River subbasin and Upper Colorado River subbasin. Green River estimates are the sum of estimates for 916 km of the Middle Green, Lower Green, Yampa, and White rivers, as well as the Desolation/Gray Canyon reach. Upper Colorado River estimates are for 292 km of the Upper Colorado River and the lower 3.5 km of the Gunnison River below the Redlands Diversion. See footnotes for data sources.

Year	Green River Subbasin[a]			Upper Colorado River Subbasin[b]		
	Estimate	Low 95% C.I.	High 95% C.I.	Estimate	Low 95% C.I.	High 95% C.I.
1991	2923					
1992	3002	--	--	440	251	832
1993	3062	--	--	705	448	1,181
1994	3354	--	--	687	508	955
1995	3272	--	--	--	--	--
1996	3679	--	--	--	--	--
1997	3352	--	--	--	--	--
1998	3441	--	--	583	462	758
1999	3900	--	--	589	466	764
2000	4206			773	562	1,095
2001	3698			--	--	--
2002	3676			--	--	--
2003	3131			661	452	990
2004		--	--	688	511	946
2005		--	--	897	737	1111
2006	2542	--	--			
2007	2339	--	--			
2008	3000	--	--	685	534	895
2009		--	--	512	410	653
2010		--	--	476	386	599
2011	2083	1674	2619			
2012	1787	1440	2242			
2013	2128	1472	3117	332	242	471
2014	--	--	--	482	360	665
2015	--	--	--	429	334	561

[a] Estimates for 1991−2008 (K. Bestgen 2014, Pers. Com.), 2011-2013 (Bestgen et al. 2018); see Table 3 for estimates from CPUE data starting in 1991.

[b] Estimates for 1992-2010 (Osmundson and White 2014); estimates for 2005-2015 were revised because of a change in PIT tag types (400 vs. 134 kHz) and the effect on detection of tagged vs. untagged fish (D. Ryden 2016, Pers. Com.).

Table 3. Estimated pikeminnow abundance, 1991-1999 for reaches of the Green River Subbasin, based on ISMP CPUE data (yellow highlight) and mark-recapture population estimates for 2000-2013. Green highlight reflects average adult pikeminnow abundance for the Desolation/Gray reach, where no ISMP data were collected. Table from K. Bestgen (Pers. Com. 2016).

Year	Middle Green River	Lower Green River	Yampa River	White River	Desolation/ Gray Canyon	Green River Subbasin
1991	1041	361	283	569	669	2923
1992	1016	383	312	622	669	3002
1993	1094	408	296	595	669	3062
1994	1274	455	290	667	669	3354
1995	1128	451	296	728	669	3272
1996	1538	494	281	699	669	3679
1997	1144	412	324	804	669	3352
1998	1270	426	368	709	669	3441
1999	1595	476	335	825	669	3900
2000	1744	444	312	1038	669	4206
2001	1423	352	357	923	642	3698
2002	1141	282	357	930	966	3676
2003	952	300	320	669	889	3131
2004	--	--	--	--	--	--
2005	--	--	--	--	--	--
2006	1089	392	135	360	567	2542
2007	702	573	120	502	442	2339
2008	804	622	100	584	890	3000
2009	--	--	--	--	--	--
2010	--	--	--	--	--	--
2011	449	356	85	696	498	2083
2012	422	335	123	274	634	1787
2013	981	244	48	365	489	2128

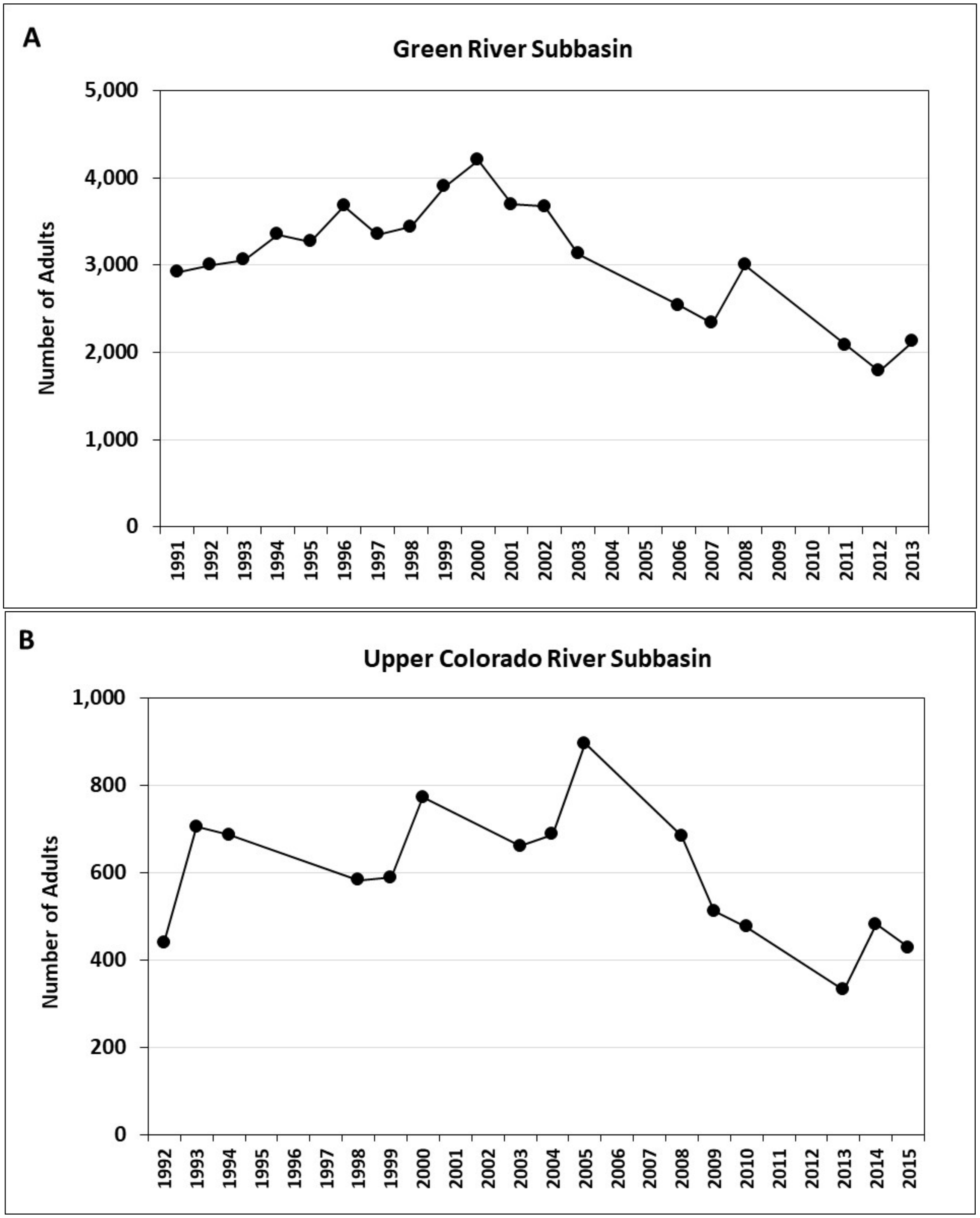

Figure 2. Annual mark-recapture population estimates for adult Colorado Pikeminnow (age 7+, ≥ 450 mm TL) in the (A) Green River subbasin and (B) Upper Colorado River subbasin. See Tables 2 and 3 for estimates and sources of data.

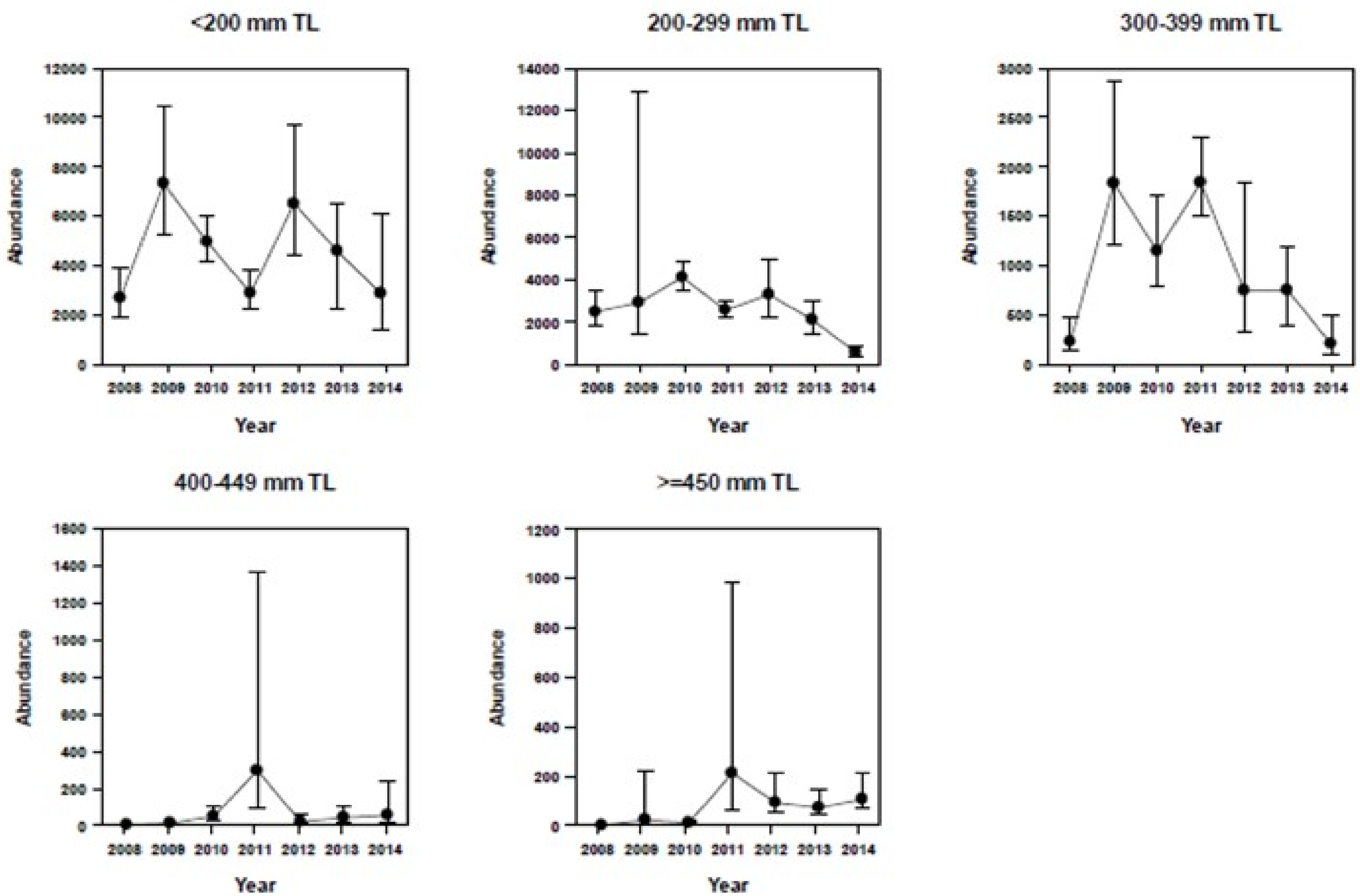

Figure 3. Closed capture abundance estimate of Colorado Pikeminnow based on first-ranked model each year. Each panel represents the abundance of Colorado Pikeminnow < 200 mm TL, 200-299 mm TL, 300-399 mm TL, 400-449 mm TL, and ≥ 450 mm TL by year 2008-2014. Error bars represent 95% confidence interval (Figure 6 from Durst 2015; table of point estimates and confidence intervals not available).

Table 4. Population estimates for juvenile Colorado Pikeminnow > 150 mm TL in the lower San Juan River from 2004 to 2013. Population estimates in 2014 were done from RM 94-53 (middle) and RM 53-3 (lower). Models used include the null model (Mo) and the time variable model (Mt) from Program Capture. CI represents 95% confidence interval. CV indicates the coefficient of variation, and p-hat represents capture probability (from Hines 2015, Table 3).

Year	Passes	Model	Estimate	CI	CV	p-hat
2004	1-2	Lincoln-Peterson	160	17-303	-	-
	1-3	Mo	315	218-545	0.22	0.07
	1-5	Mo	183	99-469	0.38	0.09
	4-6	Mo	195	124-372	0.27	0.13
	5-8	Mt	157	100-297	0.26	0.1
2005	1-3	Mo	536	288-1,283	0.37	0.06
	1-4	Mt	537	321-1,064	0.30	0.06
	1-6	Mt	696	454-1,189	0.24	0.03
	3-6	Mt	582	293-1,556	0.41	0.04
	7-9	Mo	681	241-3,950	0.67	0.03
2006	1-3	Mo	202	112-2,135	0.94	0.03
	4-6	Mo	124	78-237	0.30	0.14
	7-9	Mt	976	237-4,775	0.94	0.02
	7-10	Mt	1267	417-4,296	0.67	0.02
	1-10	Mt	455	340-640	0.16	0.04
2007	1-3	Mt	238	148-436	0.29	0.1
	7-9	Mo	68	36-180	0.31	0.13
	1-9	Mt	296	233-399	0.14	0.06
	1-10	Mt	326	257-433	0.13	0.05
2008	1-5	Mt	470	358-652	0.15	0.09
	6-9	Mt	270	149-636	0.36	0.07
	1-9	Mt	572	450-715	0.12	0.05
2009	1-4	Mo	1078	965-1222	0.06	0.16
	6-9	Mt	1221	678-2335	0.33	0.03
	1-4 and 6-9	Mt	1452	1306-1633	0.06	0.07
2010	1-7	Mo	1100	1022-1193	0.04	0.13
	1-9	Mo	1273	1185-1377	0.04	0.1
2011	1-5	Mt	1010	863-1207	0.09	0.1
	1-9	Mt	1160	1014-1348	0.07	0.06
2012	1-8	Mt	666	480-965	-	0.025-0.07
2013	5-9	Mt	862	609-1276	-	0.02-0.11
2014	Lower	Mo	185	148-250	0.14	0.17
2014	Middle	Mo	398	246-704	0.28	0.06

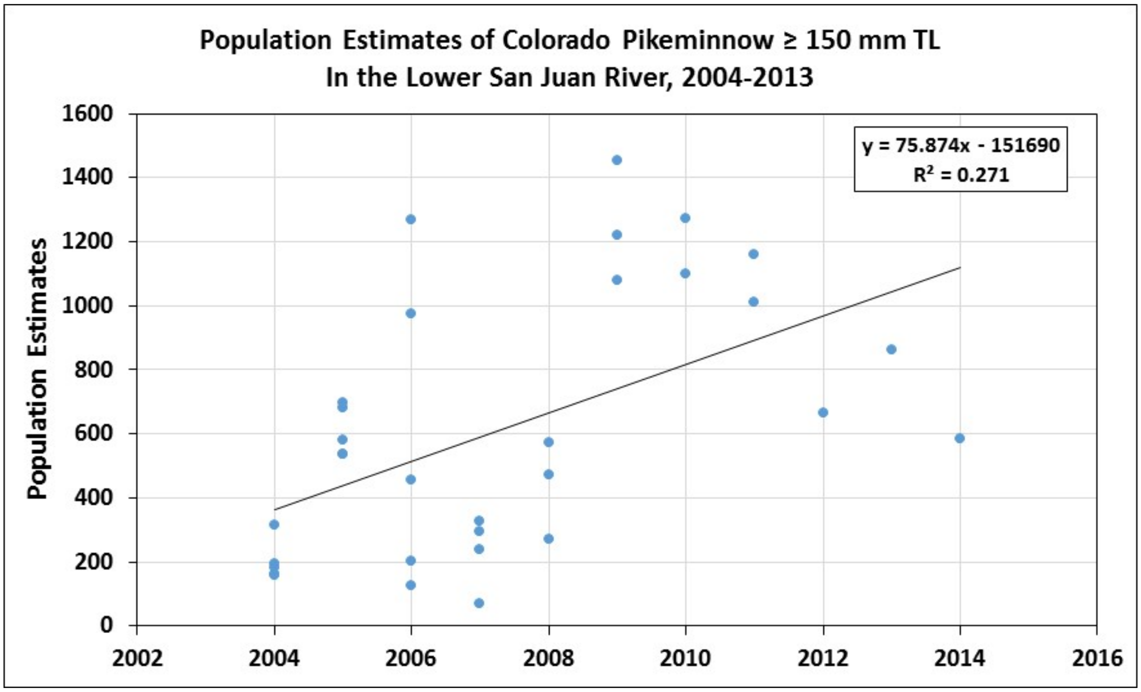

Figure 4. Population estimates for juvenile Colorado Pikeminnow > 150 mm TL in the lower San Juan River (RM 94-3) from 2004 to 2013. Population estimates in 2014 were done from RM 94-53 (middle) and RM 53-3 (lower). See Table 4 for data points.

3.0 Intrinsic Rate of Population Change (Lambda)

3.1 Green River Subbasin

Rate of population change for Colorado Pikeminnow in the Green River (1991-2013, 1991-2000, and 2000-2013), based on natural log transformed abundance estimates (from Table 3), were 0.978, 1.036, and 0.945, indicating that adult numbers changed annually by about -2.2%, +3.6%, and -5.5%, respectively, for the periods indicated (Figure 5).

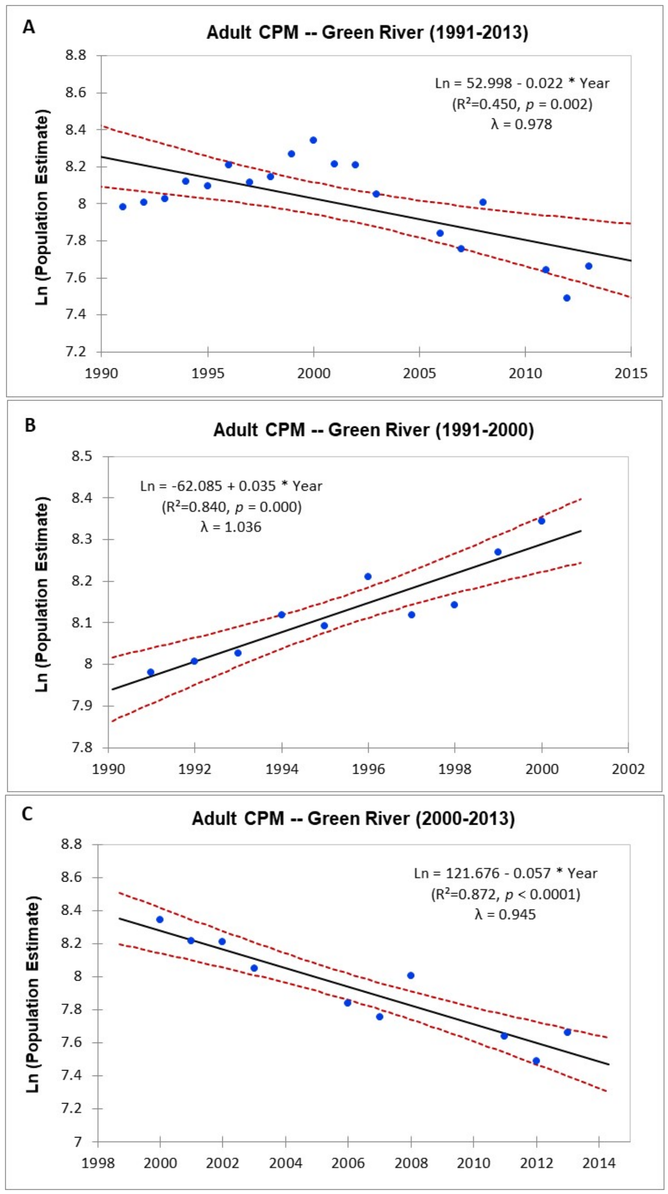

Figure 5. Intrinsic rate of population change (λ) for adult Colorado Pikeminnow (age 7+, ≥ 450 mm TL) in the Green River subbasin using population estimates (transformed to natural logarithms) for (A) 1991-2013, (B) 1991-2000, and (C) 2000-2013. Parabolic bands represent 95% confidence bounds for the linear regression. See Table 3 for population estimates and sources of data.

An annual rate of change was also computed by Bestgen et al. (2007) from the Interagency Standardized Monitoring Program (ISMP) data collected at 10 sites in the Green River from 1991 to 2003 (Figure 6).

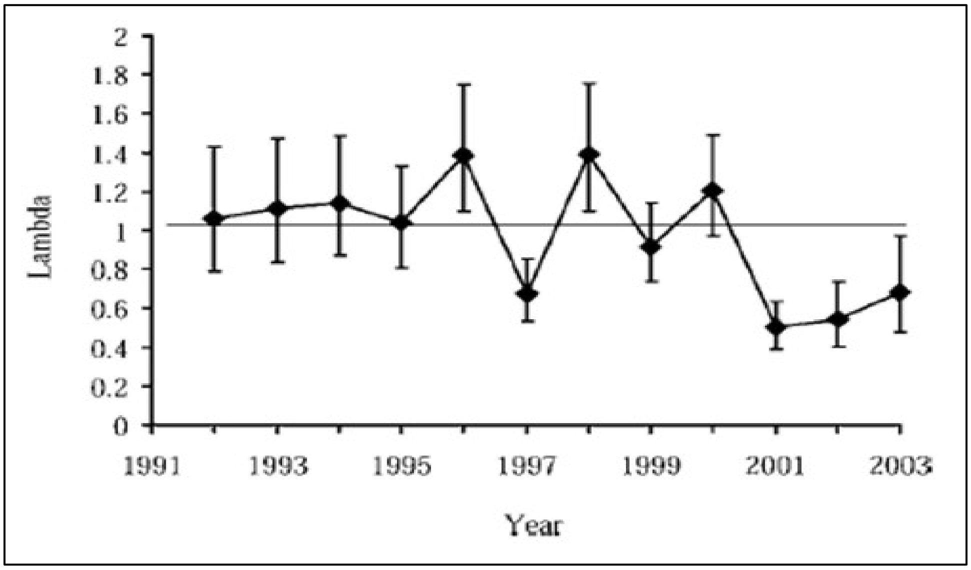

Figure 6. Estimated finite rate of population change (lambda) from ISMP data collected at 10 sites in the Green River basin from 1991 to 2003. Error bars represent 95% confidence intervals. Values of lambda greater than 1 indicate an expanding population, values less than 1 a declining population, and values of 1 a stable population (Figure 7 from Bestgen et al. 2007).

3.2 Upper Colorado River Subbasin

Intrinsic rate of population change for Colorado Pikeminnow in the Colorado River (1992-2015, 1992-2005, and 2005-2015), based on natural log transformed population estimates, were 0.985, 1.025, and 0.927, indicating that adult numbers changed annually by about -1.5%, +2.5%, and -6.3%, respectively, for the periods indicated (Figure 7).

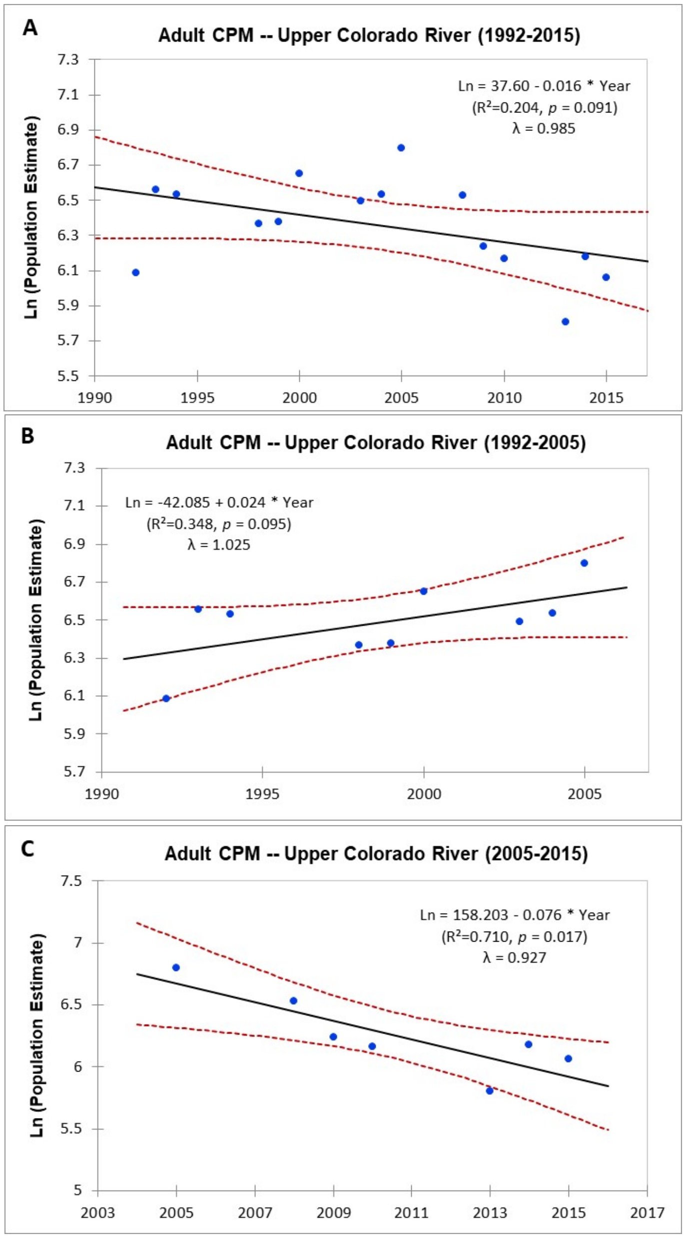

Figure 7. Intrinsic rate of growth (λ) for adult Colorado Pikeminnow (age 7+, ≥ 450 mm TL) in the Upper Colorado River subbasin for mark-recapture population estimates (transformed to natural logarithms) during (A) 1992-2015, (B) 1992-2005, and (B) 2005-2015. Parabolic bands represent 95% confidence bounds. See Table 1 for population estimates and sources of data.

3.3 San Juan River Subbasin

Intrinsic rate of population change was not computed for Colorado Pikeminnow in the San Juan River Subbasin because the number of individuals are influenced by stocked fish, and there is not much recruitment currently taking place.

4.0 Carrying Capacity (K)

4.1 Green River Subbasin

Carrying capacity of the Colorado Pikeminnow populations is unknown but some inference is provided by estimates of abundance and changes in body condition. During 1986–2000, the mean electrofishing catch rate of subadults and adults in the Green River increased steadily by four times from 0.9 fish/hr to 3.6 fish/hr (McAda et al. 1997), and the relative condition of adults declined, suggesting that the population was approaching carrying capacity. The number of adults at maximum density was estimated at 4,206 adults in 2000 (Bestgen et al, 2005), or about 7.4 adults/mi (4,206/569 mi).

4.2 Upper Colorado River Subbasin

Osmundson and White (2013) suggested that carrying capacity of the Upper Colorado River differs between the upper reach (106 km, 66 mi) and lower reach (180 km, 112 mi), primarily because of food availability (i.e., small-bodied forage fish), which is 4.5 times higher in the upper reach. The upper reach is upstream of Westwater Canyon, including the lower 3.5 km of the Gunnison River below the Redlands Diversion, and the lower reach is downstream of Westwater Canyon. It was determined that 7.2 adults/km (11.6 adults/mi) was a rough estimate of adult densities that the upper reach might support. It was also surmised that a density of 2.7 fish/km (4.4 fish/mile) was associated with a decline in body condition and reflected possible carrying capacity in the lower reach. The number of adults at maximum density was estimated at 897 adults in 2005, or about 5.0 adults/mi (897/181 mi). Osmundson and White (2013) concluded that population abundance in the Upper Colorado River is not currently limited by carrying capacity but rather by insufficient recruitment due to a low frequency of strong or moderately-strong year classes.

4.3 San Juan River Subbasin

Miller and Lamarra (2006) developed a population model for the San Juan River through the use of bioenergetics which included an estimate of the carrying capacity of Colorado Pikeminnow. Using this model, they estimated that 800 adults (> 450mm TL) could be sustained in the San Juan River. This preliminary estimate was based on prey availability data collected only in the upper-most reach of critical habitat (geomorphic reach 6; Bliesner and Lamarra 2000). This estimate was based on the assumption that ongoing removal of Channel Catfish and Common Carp would allow small-bodied prey species to increase in numbers to densities similar to those found in reach 6, where Common Carp and Channel Catfish were absent and/or rare at the time. However, after 15 years of non-native fish removal, this assumption has been disproven and densities of small-bodied fish continue to be low downstream of reach 6.

Following these findings, carrying capacity of Colorado Pikeminnow for the San Juan River was recalculated in 2013 using the estimated densities of prey for each of the six reaches (Figure 8, Table 5). Based on these data, it was surmised that carrying capacity of would decrease similar to prey availability among reaches. The revised carrying capacity for the 180 mi (290 km) of river is 406 adults, or about 2.3 fish/mi (1.4 fish/km; Table 2; Miller 2013). Key uncertainties for this estimate are densities of small-bodied fishes and the ability of Colorado Pikeminnow to utilize these as a forage base.

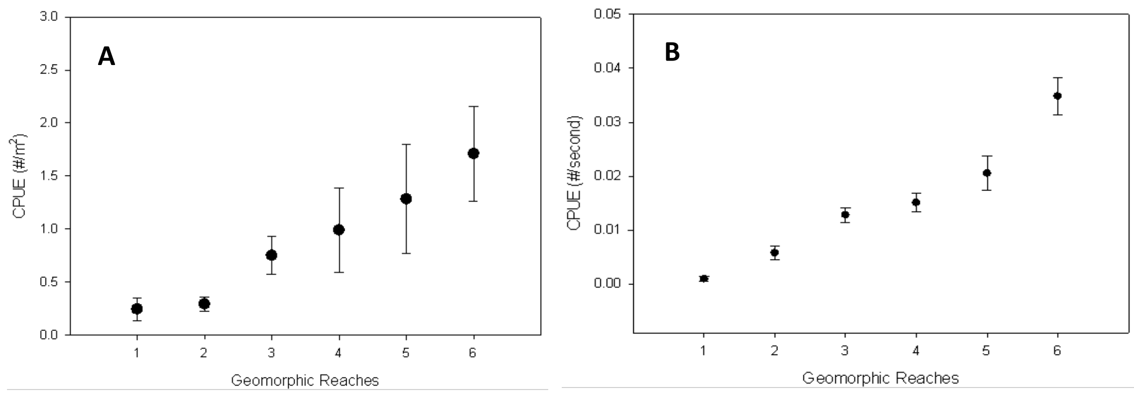

Figure 8. Catch rate (CPUE) of forage fishes in six reaches of the San Juan River: (A) small-bodied fishes caught by seining of backwaters, secondary channels, and the primary channels, 2003-2011, and (B) juvenile fishes caught by electrofishing, 2003-2012. Mean +/-1 standard error (SE). Figures provided by the San Juan River Basin Recovery Implementation Program.

Table 5. Estimated carrying capacity of adult Colorado Pikeminnow in six geomorphic reaches of the San Juan River (Miller 2013). River miles are measured from Piute Farms (RM 0.0) upstream to about the confluence of the Animas River (RM 180.0).

Reach	Length (miles)	Total Adults	Number of adults/mile
1	0-16 (16)	16	1
2	17-67 (51)	51	1
3	68-105 (38)	38	1
4	106-130 (25)	75	3
5	131-154 (24)	96	4
6	155-180 (26)	130	5
Totals:	**180**	**406**	**2.3**

When maximum estimated population sizes are based on lengths of river sampled and compared among river basins, the number of adult Colorado Pikeminnow per mile is highest for the Green River (7.4 fish/mi), compared to the Upper Colorado River (5.0 fish/mi) and the San Juan River (2.3 fish/mi; Table 6). This indicates that maximum observed density of adult Colorado Pikeminnow in these three river subbasins is quite different.

Table 6. Estimated maximum density of adult Colorado Pikeminnow for reaches included in abundance estimates. Estimate for the San Juan River is based on a bioenergetics model and not on number of fish currently in the system.

Subbasin	River Km (miles)	Highest Estimate	No./km	No./mi
Green River	916 (569)	4,206	4.6	7.4
Upper Colorado River	292 (181)	897	3.1	5.0
San Juan River	290 (180)	406	1.4	2.3

5.0 Age and Growth

5.1 Maximum Size and Age

The oldest Colorado Pikeminnow documented from scale annuli were 11 years (610 mm TL) from the Green River (Vanicek and Kramer 1969; Seethaler 1978); 16 years from the White River; 12 years from the Upper Colorado River (Hawkins 1992); and 13 years (879 mm TL; Musker 1981) and 18 years (2 fish average of 804 mm TL; Hawkins 1992) from the Yampa River. Osmundson et al. (1997) cautioned that scale-based age estimates are probably unreliable for Colorado Pikeminnow beyond about age 10, and concluded from growth-rate data that large fish (e.g., > 900 mm TL) average 47–55 years old with a minimum age of 34 years. The discrepancy in age determination has not been resolved, but scale-based age determination may not be reliable because of closely-spaced and indistinguishable annular rings caused by slowed growth of old fish, and possibly because scale resorption erodes, distorts, or eliminates one or more annular rings.

It appears that the first scale annulus does not form on the Colorado Pikeminnow, and the first visible annulus reflects the second winter of life (Musker 1981; Hawkins 1992). Average length at the end of the second annulus formation ranged 90–123 mm TL (Hawkins 1992). The maximum length of fish collected in the wild is just over 800 mm TL. Asymptotic lengths, based on scale back-calculations and derived from Walford plots, indicate that maximum potential length of Colorado Pikeminnow in the upper basin is 1,152 mm TL (Hawkins 1992). Historical accounts of fish in the lower basin indicate a maximum length of about 1,800 mm TL. Kaeding and Osmundson (1989) hypothesized that growth and overall size of Colorado Pikeminnow in the upper basin is limited by a more restrictive and cooler temperature regimes than in the lower basin.

5.2 Age and Size at Maturity

Vanicek and Kramer (1969) found that nearly all fish from the Green River age 7 and older (estimated at 454 mm TL from scale back-calculated lengths) were sexually mature. Seethaler (1978) determined that age-7 Colorado Pikeminnow from the Green and Yampa rivers averaged 451 mm TL (scale back-calculations). He also necropsied 147 Colorado Pikeminnow between 184 and 652 mm TL and found that all fish longer than 503 mm TL were sexually mature, and fish less than 428 mm TL were immature; 76% of 34 fish examined between 428 and 503 mm TL were sexually mature. Hamman (1986) found that hatchery-reared Colorado Pikeminnow were sexually mature at age 5 (males) and age 6 (females) at total lengths of 317–376 mm and 425–441 mm, respectively. Osmundson et al. (1997) found that all fish examined were sexually mature at age 7 or 450 mm TL. Osmundson (2006) further examined wild fish and found that males were mature at 6 years and females were mature at 8 years; males spawned as early as 6 years with most at 8 years; most females did not spawn until age 9 and more likely 10 years of age.

5.3 Growth Rate

Age at length information for Colorado Pikeminnow is available from several sources (Vanicek and Kramer 1969; Seethaler 1978; Musker 1981; Hawkins 1992; Osmundson 2002). Larvae at hatching are 6.0–7.5 mm long (Hamman 1981) and average about 40 mm TL (range, 29–47 mm) in October at about 3 months of age (Valdez 1990; Tyus and Haines 1991). Growth under laboratory conditions averaged about 13 mm/30 days (Hamman 1981). Growth of adults in the Green River was about 10.2 mm/year (Tyus 1988). Mean annual growth rate of fish from the Upper Colorado River aged 3–6 years ranged from 32.2 (age 6) to 82.0 (age 3) mm/year and declined to 19.8 mm/year for fish 500–549 mm TL (Osmundson et al. 1997); fish ≥ 550 mm TL grew an average of 9.5 mm/year. Preliminary evidence indicates that females grow larger and perhaps live longer than males (Vanicek 1967; Tyus and Karp 1989).

Hawkins (1992) surmised that because Colorado Pikeminnow hatch in late summer, they either fail to form scales in their first winter or fail to form a first annulus. He assumed that all previous studies had missed the first annulus, and determined that age-7 fish averaged 396 mm TL, and age-8 fish averaged 440 mm TL. Hawkins defined mature Colorado Pikeminnow as fish over 428 mm TL, based primarily on findings of Seethaler (1978). Osmundson et al. (1997) used growth-rate data from mark-recapture information and scale back-calculations from fish of the Upper Colorado River subbasin and determined that age-7 Colorado Pikeminnow averaged 456 mm TL (range, 430–479 mm TL). Mark-recapture, growth-rate data from Osmundson (2002) were also used to develop length to age relationships. Based on the best available information on age at sexual maturity and age to length relationships, adult Colorado Pikeminnow are defined as fish that are 450 mm TL or larger. This is based on the conservative assumption that all age-7 fish are sexually mature, and average length at age 7 is 450 mm TL. Subadults (age 6) are defined as those fish that are 400–449 mm TL.

A list of von Bertalanffy parameters for Colorado Pikeminnow from different rivers of the upper basin is presented in Table 7, and the graphical representations of each are presented in Figure 9. The $L\infty$ is the theoretical maximum length of the fish, the K is the growth coefficient or the annual rate of growth, and t_o is the point in time at which the fish has zero length.

The growth rates illustrated in Figure 9 are for wild Colorado Pikeminnow from various rivers of the Upper Colorado River Basin. Growth rates of wild Colorado Pikeminnow from the San Juan River are not determined because of the small numbers of wild fish. A large number of age-0 Colorado Pikeminnow (6–8 months of age) are stocked into the San Juan River annually and the growth rate of these known-age fish appears similar to wild upper basin fish (Figure 10). However, stocked fish are larger than wild fish of the same age and age-at-length for Colorado Pikeminnow from the San Juan River appears to be different than wild fish from the upper basin.

Table 7. Growth parameters of Colorado Pikeminnow for von Bertalanffy function.

Citation	Years	River	n	L∞	K	t_o
Vanicek and Kramer (1969)	1964-66	Green	182	1144	0.07475	0.64959
Seethaler (1978)	1974-76	Green	68	752	0.15767	1.29628
Musker (1981)	1979-81	All	139	1147	0.08611	1.01437
Hawkins (1992)	1978-90	Green	116	1246	0.05347	0.43075
Hawkins (1992)	1978-90	White	48	781	0.09543	0.25031
Hawkins (1992)	1978-90	Yampa	148	1221	0.06675	0.60655
Hawkins (1992)	1978-90	Combined	326	1152	0.06293	0.58136
Osmundson and White (2014)	2004-2010	Colorado	721	814	0.0873	0.68988
SJR Database (Pers. Com. N. Franssen, 2016)	1997-2014	San Juan	1135	794	0.175	-0.255

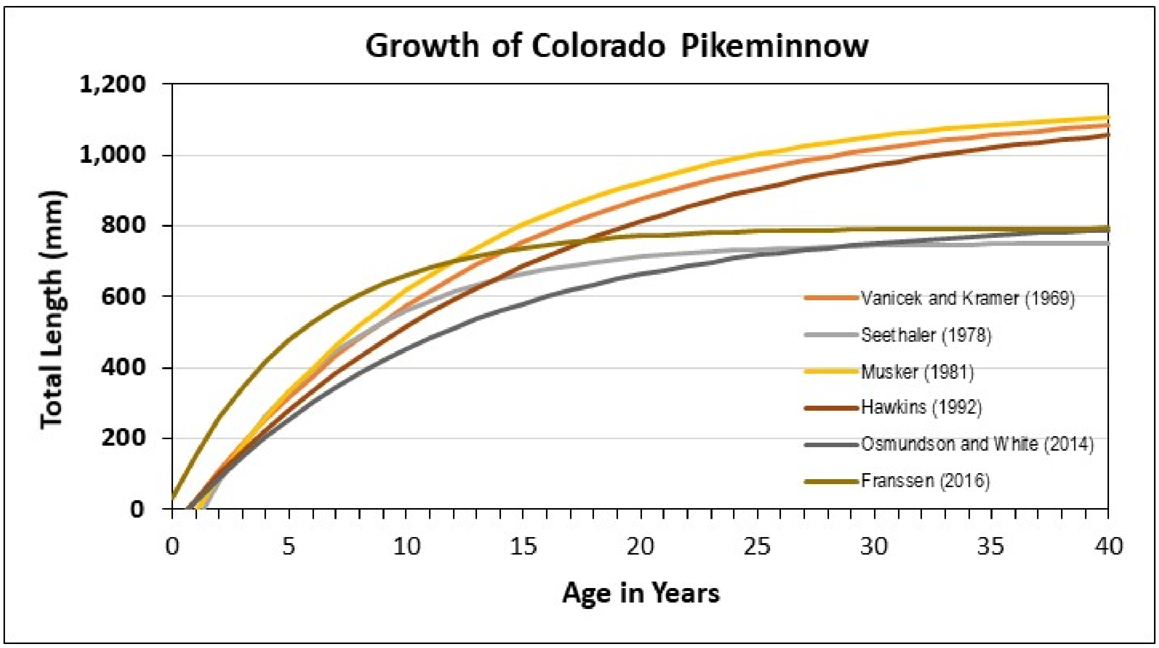

Figure 9. Predicted length at age for Colorado Pikeminnow computed from von Bertalanffy growth function. Based on parameters in Table 9 from Vanicek and Kramer (1969), Seethaler (1978), and Musker (1981) as presented in Hawkins (1992); from Osmundson and White (2014), and from the San Juan River (SJR) Database (Pers. Com. N. Franssen 2016).

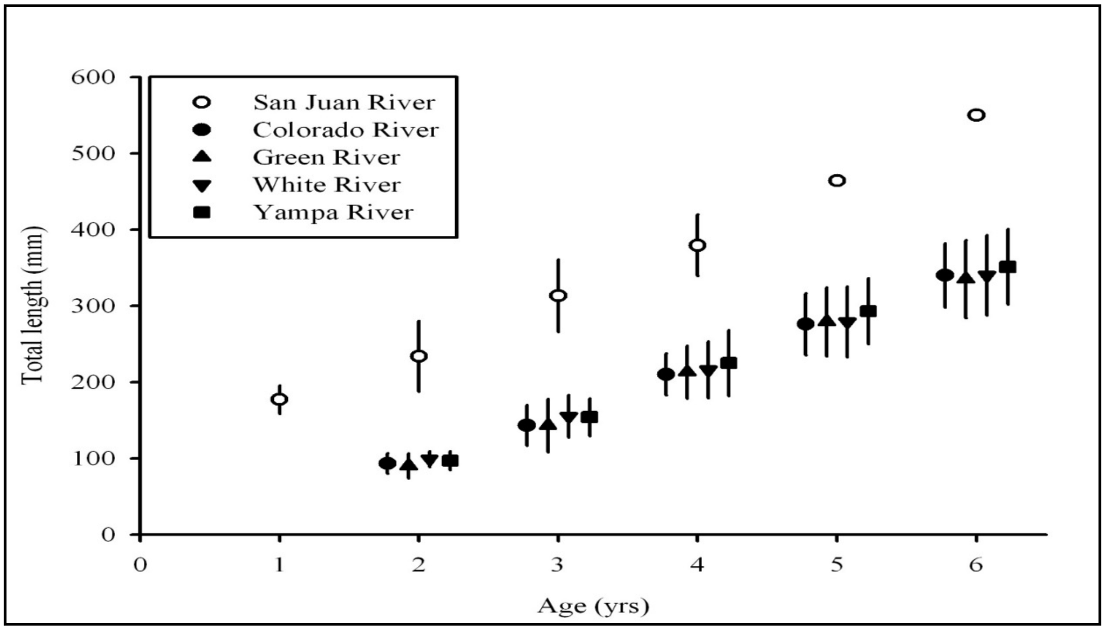

Figure 10. Mean lengths of age 1–6 Colorado Pikeminnow stocked in the San Juan River as age-0, compared to mean lengths of wild fish from rivers of the Upper Colorado River Basin. Figure provided by S. Durst (USFWS).

5.4 Effect of Temperature and Predator Density on Growth

Baseline growth rates for young fish adjusted for water temperature: GRdaily = GRbaseline [(-0.279 + 0.0387T – 0.000637T2) / 0.283]; baseline growth rates were 0.41 mm/d TL for fish in the middle Green River in 1991 and 0.43 mm/d in 1992, and daily growth rates in the lower Green River were 0.44 mm/d in 1991 and 0.31 mm/d in 1992 (Figure 11; Bestgen et al. 2006).

Larvae that arrived midseason in backwaters encountered the best conditions for survival because temperatures were warm and predators were relatively small; larvae experienced up to 30 d of rapid growth to sizes that were not susceptible to predation; later-hatching larvae encountered smaller predators but experienced slower growth because of declining water temperature (Figure 12; Bestgen et al. 2006). See also Figure 27 in Predation and Competition.

Within given cohorts, mean growth rates of summer juveniles were lower than mean growth rates of autumn juveniles (Figure 12); suggesting that CPM surviving to autumn represented fastest growing subset of summer juveniles (Bestgen et al. 2006)

In simulations of Red Shiner predation, water temperature had a large and positive effect on mean growth rate of larvae; 0.2 to 0.6 mm/d TL reflected range found for wild age-0 fish (0.15–0.65-mm/d TL) (Figure 13; Bestgen et al. 2006).

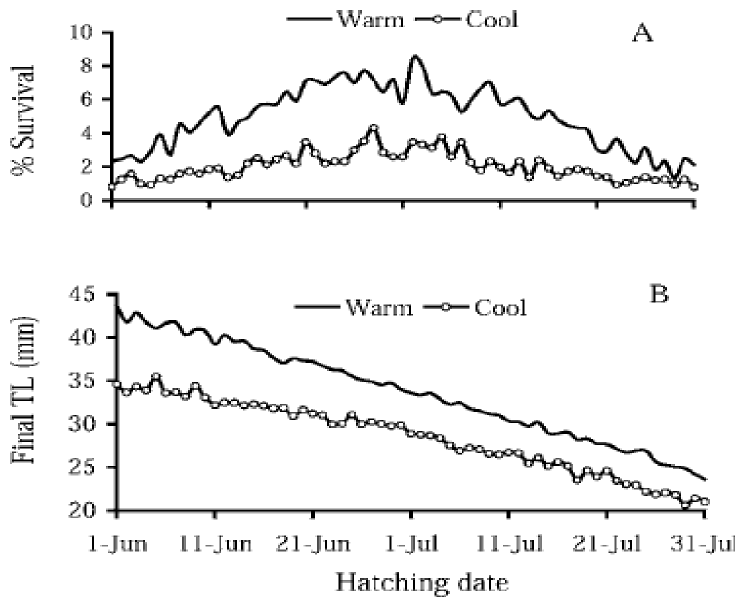

Figure 11. Simulated effects of cool and warm thermal regimes and hatching date on (A) survival and (B) final total length (TL) of Colorado Pikeminnow larvae that hatched from 1 June to 1 August in the Green River, Utah. Simulations ended 1 October, and predator density was 6 Red Shiners/m². **Figure 8 from Bestgen et al. 2006.**

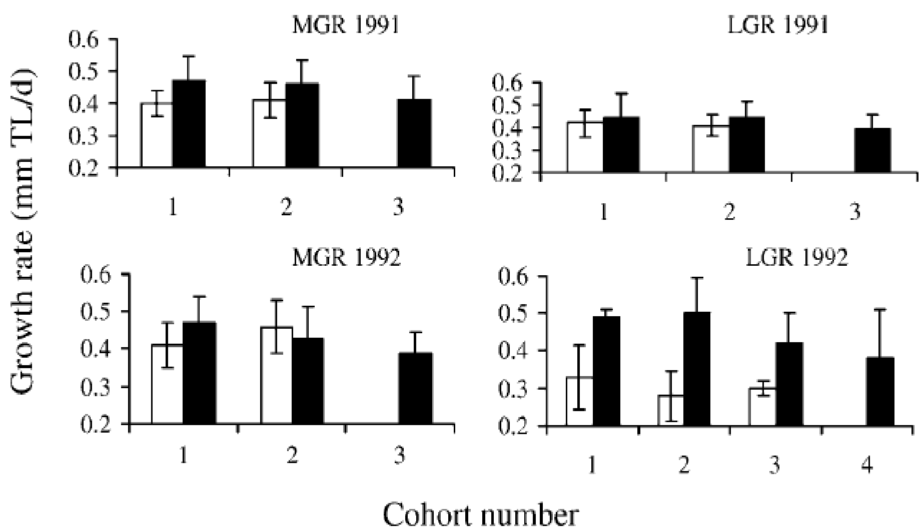

Figure 12. Presumed effects of size-selective predation on mean growth rate (total length) of summer and autumn juvenile Colorado Pikeminnow for each of the three or four within-year cohorts, comparing summer (white bars) and autumn (black bars) in the middle (MGR) and lower Green River (LGR), Utah, in 1991 and 1992; whiskers = SDs. The single summer sample was collected before fish in the third cohort (fourth cohort in the case of the lower Green River in 1992) hatched, so there was no corresponding summer sample for those cohorts. Figure 7 from Bestgen et al. 2006.

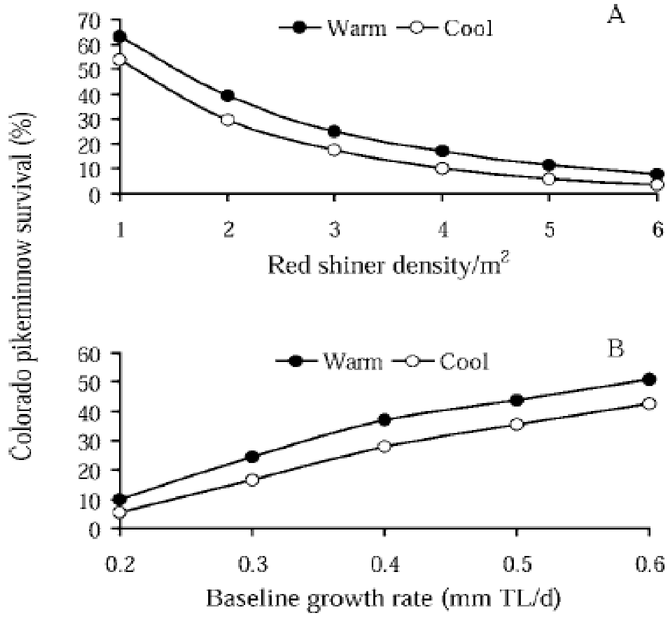

Figure 13. Simulated effects of (A) Red Shiner predator density and (B) Colorado Pikeminnow baseline growth rate on survival of age-0 cohorts of pikeminnow larvae in the Green River, Utah, using warm and cool thermal regimes. Colonization date was 1 July. Figure 9B from Bestgen et al. 2006.

5.5 Generation Time

Generation time is the average age at which a female gives birth to her offspring, or the average time for a population to increase by a factor equal to the net reproductive rate. Generation time (GT) is computed as:

$$GT = age_{sSM} + (1/d),$$

where: age_{sSM} = average age at sexual maturity, and

d = death rate (Seber 1982; Gilpin 1993).

Osmundson (2006) estimated that males spawn as early as 6 years with most at 8 years; and that most females do not spawn until age 9 years and more likely 10 years. Hence, generation time for Colorado Pikeminnow was computed from an average age of sexual maturity (8 years) and the annual adult survival rate (0.80; see section 5.0 Survival):

$$GT = 8 + [1/(1-0.80)] = 8 + 5 = 13 \text{ years}.$$

6.0 Length and Weight

6.1 Maximum Size

The Colorado Pikeminnow is a warm-water riverine fish species found only in the Colorado River System of North America. It is the largest minnow native to North America with an estimated length of 1.8 m and a weight of 36 kg (Miller 1961). The species is presently restricted to the cooler Upper Colorado River Basin where the largest fish found today are about 1 m in length and weigh about 12 kg (Figure 14; USFWS 2002).

Figure 14. Adult Colorado Pikeminnow captured at the Redlands Diversion fish passage on the Gunnison River and released alive and unharmed; approximate size of fish = 1 m and 12 kg. Photo by Bob Burdick, U.S. Fish and Wildlife Service.

6.2 Length and Weight Relationships

Length-weight relationships for Colorado Pikeminnow from four rivers in the upper basin are presented for length (L) and weight (W) and shown in Figure 15:

- Green River, $Log_{10}W = -5.692 + 3.206 * Log_{10}L$,
- Colorado River, $Log_{10}W = -6.384 + 3.463 * Log_{10}L$,
- Yampa River, $Log_{10}W = -6.026 + 3.339 * Log_{10}L$,
- White River, $Log_{10}W = -5.555 + 3.156 * Log_{10}L$,
- San Juan River (Jan-May), $Log_{10}W = -5.1707 + 3.0005 * Log_{10}L$, and
- San Juan River (Jun-Sep), $Log_{10}W = -5.2666 + 3.0405 * Log_{10}L$.

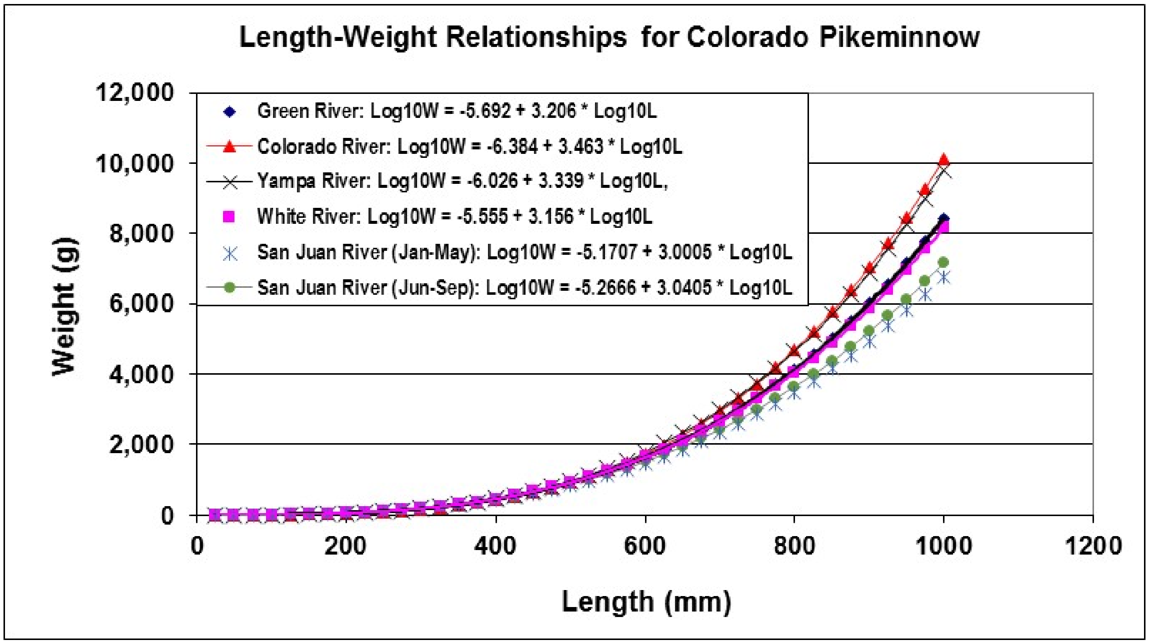

Figure 15. Length-weight relationships for Colorado Pikeminnow of the Green, Colorado, Yampa, and White rivers (Hawkins 1992), and the San Juan River (Pers. Com. N. Franssen 2016).

Slopes and parameters of length-weight relationships were not significantly different among rivers (Hawkins 1992); similar relationships were provided by Vanicek and Kramer (1969), Seethaler (1978), and N. Franssen (Pers. Com. 2016). Exponents > 3.0 suggest allometric growth in Colorado Pikeminnow; i.e., the relationship of weight as a cube of the length (exponent > 3.0) changes as the fish grows, whereas exponents of ≤ 3.0 indicate isometric growth or a constant relationship between length and weight (Lagler 1956).

Mean relative condition of adult Colorado Pikeminnow (> 428 mm TL) ranged from about 0.92 to about 1.12 (Hawkins 1992). Highest condition usually occurred in June and was probably related to increase in fat reserves or gametes in preparation for spawning. Lowest condition occurred in July and August following pre-spawning migration and spawning activity. Condition usually increased in fall after the migratory period when fish returned to their home ranges.

Length-weight relationships were also computed for Colorado Pikeminnow during a period of population increase (1991-1999) and during a period of population decline (2000-2003) (Bestgen et al. 2006):

- During population increase (1991-1999): $Log_e W = -12{:}365 + 3{:}105 * Log_e (TL)$.
- During population decline (2000-2003): $Log_e W = -12{:}20 + 3{:}068 * Log_e (TL)$.

7.0 Fecundity, Hatching, and Temperature

7.1 Fecundity

Fecundity is defined in this document as the number of eggs produced by a female as indicated by the number of eggs manually stripped from a fish. The number of eggs per female Colorado Pikeminnow varies considerably as reported. An estimated 55,000 eggs were manually stripped from five injected wild fish for an average of 11,000 eggs/fish; at an average fish size of 681 mm TL and 2,824 g, fecundity was 3,895 eggs/kg (Table 8; Hamman 1981). Fecundity of 10 injected hatchery-reared females was 78,540 eggs for an average of 10,542 eggs/kg.

Table 8. Summary of spawning data for Colorado squawfish at Dexter National Fish Hatchery, New Mexico. Table from Hamman (1981).

Locale: Fish	Fish Age	Fish Size	Average Eggs/Fish	Eggs/kg	Citation
WBNFH[a]: 5 injected wild females	unknown	681 mm TL 2,824 g	55,000 / 5 = 11,000	3,895	Hamman (1981)
WBNFH: 10 injected hatchery-reared females	6	429 mm TL 681 g	78,540 / 10 = 7,854	10,542	Hamman (1981)
DNFH[b]: 24 injected hatchery-reared females	9	1,403 g (572 mm TL)[c]	77,400 (57,766–113,341)	55,533	Hamman (1986)
DNFH: 9 injected hatchery-reared females	10	1,464 g (579 mm TL)[c]	66,185 (11,977–91,040)	45,451	Hamman (1986)

[a] WBNFH = Willow Beach National Fish Hatchery, Willow Beach, AZ.
[b] DNFH = Willow Beach National Fish Hatchery, Willow Beach, AZ.
[c] Derived from length-weight relationship for Green River: $Log_{10}W = -5.692 + 3.206 * Log_{10}L$ (Hawkins 1992).

Hamman (1986) later induced spawning of hatchery-reared Colorado Pikeminnow that were 9 and 10 years old. Average fecundity of injected hatchery-reared 9-year old females (n = 24) was 77,400 eggs (range, 57,766–113,341) or 55,533 eggs/kg, and average fecundity of 10-year old females (n = 9) was 66,185 eggs (range, 11,977–91,040) or 45,451 eggs/kg (Table 9; Hamman 1986).

Table 9. Summary of spawning data for Colorado squawfish during May-Jun 1983 and 1984 at Dexter National Fish Hatchery, New Mexico. Table from Hamman (1986).

Value	Weight of fish (g)	Eggs per female	Eggs per kg body weight
1983: 24, 9-year-old females			
Minimum	1,045	57,766	37,695
Maximum	2,045	113,341	66,452
Mean	1,403	77,400	55,533
1984: nine, 10-year-old females			
Minimum	1,182	11,977	7,984
Maximum	1,727	91,040	61,135
Mean	1,464	66,185	45,451

7.2 Temperature Requirements

The Colorado Pikeminnow is an obligate warm-water species that requires relatively warm temperatures for spawning, egg incubation, and survival of young. Spawning activity begins after the peak of spring runoff during June–August at water temperatures typically 16°C or higher (Vanicek and Kramer 1969; Hamman 1981; Muth et al. 2000). In the lower Yampa River, reproduction was initiated within days of mean daily water temperature exceeding 18°C, with water temperature at initiation ranging 16.0–22.3°C on the Yampa River and 19.8–23.0°C on the lower Green River (Bestgen et al. 1997). As a rule of thumb, Colorado Pikeminnow usually spawn at about the time of the summer solstice (Figure 16; Bestgen et al. 2006).

Colorado Pikeminnow are broadcast spawners that scatter adhesive eggs over cobble substrate which incubate in interstitial spaces. In a laboratory setting, hatching success was greatest at 20–24°C with incubation time of 90–121 h (Hamman 1981; Marsh 1985). The eggs in the wild incubate in gravels for about 5 days. Newly hatched larvae are 6.0–7.5 mm long (Hamman 1981), which emerge from spawning cobbles 3–15 days after hatching and drift predominantly as protolarvae (Haynes et al. 1984; Nesler et al. 1988).

Annual thermal units at River Mile (RM) locations of the San Juan River before (1949-1962) and after (1965-2004) construction of Navajo Dam are shown in Figure 17 (Lamarra 2007).

7.3 Sex Ratio

The information on sex ratio is highly variable because most observations have been made from field sampling during a short interval of the total spawning event. Generally, high turbidity precludes direct observation of spawners and fish are captured with trammel nets over spawning bars. Male to female ratios reported from catches over spawning bars are 9:1 (Holden and Stalnaker 1975), 13.85:1 (Tyus 1990), and 5.6:1 (Seethaler 1978). Ratios of active males to females visually observed spawning naturally under hatchery conditions are 2:1, and 2–3:1 (Hamman 1981). Colorado Pikeminnow sampled from an Upper Colorado River spawning site in 1994, 1998, and 1999 (USFWS, unpublished data) yielded 42 different fish including 21 running ripe males and one running ripe female (21:1). Inclusion of suspected males (four) and females (12), however, resulted in a ratio of 1.9:1 (the gender of four fish was undetermined).

Because of the disparate empirical data from spawning bar surveys, Lentsch et al. (1998) used a consensus of biologists at a workshop to arrive at a species-wide male:female ratio of 4.5: 1 for calculating N_e, but Crowl and Bouwes (1998) used a sex ratio of 3:1 to develop a population model for the Colorado Pikeminnow; this ratio was used in the 2002 Recovery Goals. New information shows a sex ratio of 1.11:1.0 from examination of 301 adults (> 250 mm) sampled in the Upper Colorado River subbasin in 1999 and 2000 (Osmundson 2006). The sex ratio of 1.11:1.0 is the currently acceptable ratio.

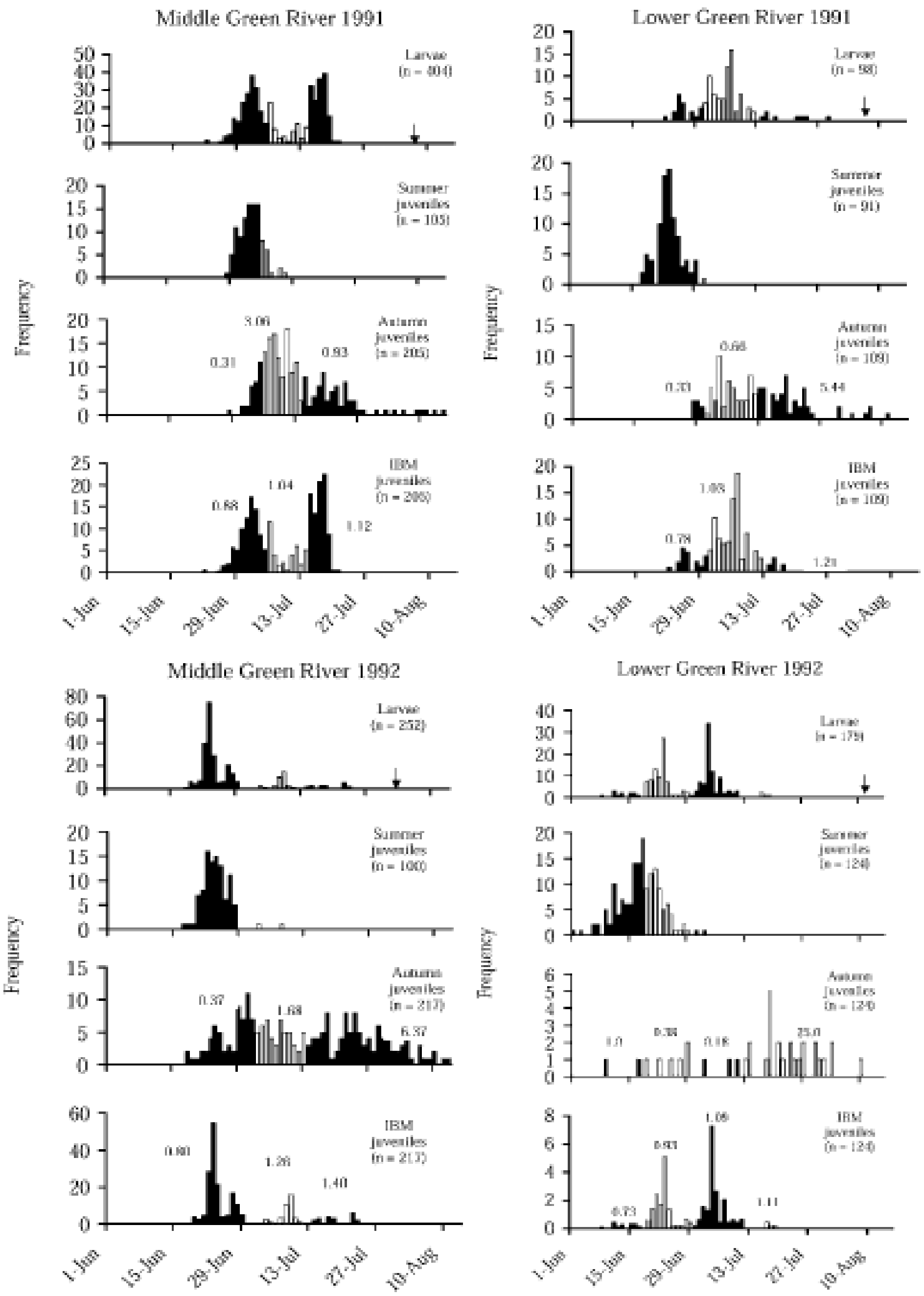

Figure 16. Distribution of hatching dates of drift-net-captured Colorado Pikeminnow larvae and seine-sampled juveniles captured in the middle and lower Green River in summer and autumn 1991 and 1992 compared with the distribution for IBM simulations using the hatching date distributions of drift-net-captured larvae as input. First cohort fish are represented by the leftmost set of black bars in each histogram, second cohort fish by the white bars, and third cohort fish by the rightmost black bars; the lower Green River in 1992 has a fourth cohort (rightmost white bars). Relative survival index values are given above each cohort for autumn juveniles captured in the field and juveniles in IBM simulations. The arrow intersecting the larval hatching date axis represents the last date drift-net samples were collected. Figure 6 from Bestgen et al. (2006).

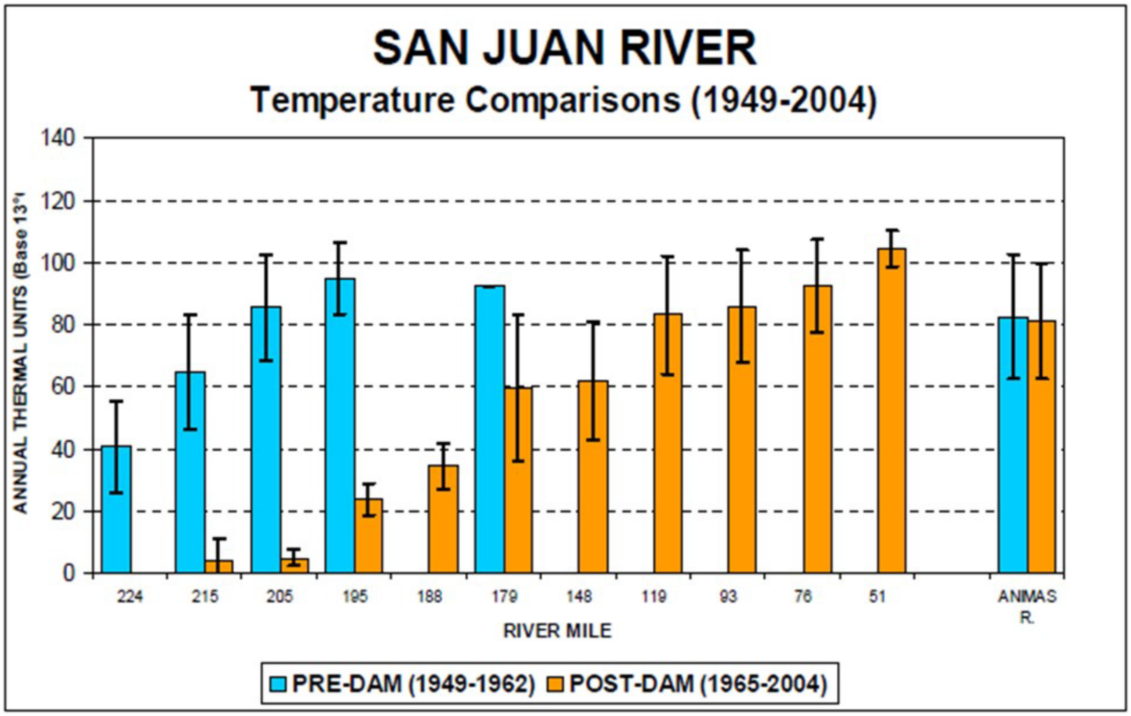

Figure 17. Annual thermal units at River Mile (RM) locations of the San Juan River before (1949-1962) and after (1965-2004) construction of Navajo Dam (pre-dam data not available upstream of the Animas River, RM 180). RM 224 = Navajo Dam, RM 180 = Animas River confluence, RM 0 = waterfall at Lake Powell inflow. Figure 8 from Lamarra (2007).

8.0 Movement and Transition

8.1 Movement

The Colorado Pikeminnow is a long-distance migratory species, classified as "potadromous" or migratory within the river basin (Tyus 1990). Recently hatched larvae in the Green River subbasin drift passively downstream for up to about 120 km before they are entrained in a nursery backwater, usually a sand bed channel or embayment Bestgen et al. 2006). The young remain in or near these nursery areas for the first 2–4 years of life; then move upstream to recruit to adult populations and establish home ranges. In the Upper Colorado River, distance moved was inversely related to fish size; displacement of fish < 550 mm TL averaged 33.6 km and displacement for fish ≥ 550 mm TL was only 7.5 km (Osmundson and Burnham 1998). Similar average movement of 31.8 km was observed for 43 radio-tagged adults during fall and spring in the Green River (Archer et al. 1985). Adult Colorado Pikeminnow remain in home ranges during fall, winter, and spring and may move considerable distances to and from spawning areas in summer. Individuals move to spawning areas shortly after runoff in early summer, and return to home ranges in August and September (Tyus 1990). Round-trip movements of up to 950 km have been reported (Irving and Modde 2000), with some fish "straying" between rivers within the Green River subbasin (Tyus 1985, 1990; Tyus and McAda 1984). Adults may return in consecutive years to overwinter in the same areas (Wick et al. 1985; Valdez and Masslich 1989).

8.2 Exchange among Subbasins

Populations of Colorado Pikeminnow in the Green River and Upper Colorado River subbasins consist of separate spawning stocks whose progeny and adults mix; nevertheless, these populations are demographically independent. Radio-tagged adults show considerable fidelity to respective spawning areas, with some exchange of individuals between these areas in different years (Tyus 1985, 1990). Although adults show fidelity to three primary spawning sites (1 each in the Yampa, Green, and Upper Colorado rivers), fish in these subbasins are linked genetically (Ammerman and Morizot 1989) through movement and exchange of individuals. Recent findings of fish in tributaries also demonstrate the potential for range expansion during high population levels (Marsh et al. 1991; Masslich and Holden 1996; Cavalli 1999; Zimmerman 2005).

The Colorado Pikeminnow in the Upper Colorado River Basin is distributed in three subbasins, where the migratory nature of the species and documented mixing of stocks indicate that the species functions as a metapopulation for two of these subbasins—the Green River and Upper Colorado River (Figure 18). The largest self-sustaining population occurs in the Green River subbasin where there is direct and unimpeded connection to tributaries, including the Yampa and White rivers (Tyus and McAda 1984), and to a smaller self-sustaining population in the Upper Colorado River subbasin.

Larvae hatched in the lower Yampa River may drift 50–120 mi downstream to nursery backwaters. High densities of age-0 Colorado Pikeminnow have been found downstream of the confluence of the Green and Upper Colorado rivers and in the Lake Powell inflow (Valdez 1990), suggesting that fish from both systems are transferred passively or move actively downstream into these regions. Osmundson et al. (1998) showed that subadult Colorado Pikeminnow in the Colorado River move back upstream as they mature. Gilpin (1993) hypothesized that this upstream return by subadults provides connectivity and gene flow between the Green and Upper Colorado rivers, resulting in a panmictic population for the entire upper basin with evidence of source/sink dynamics.

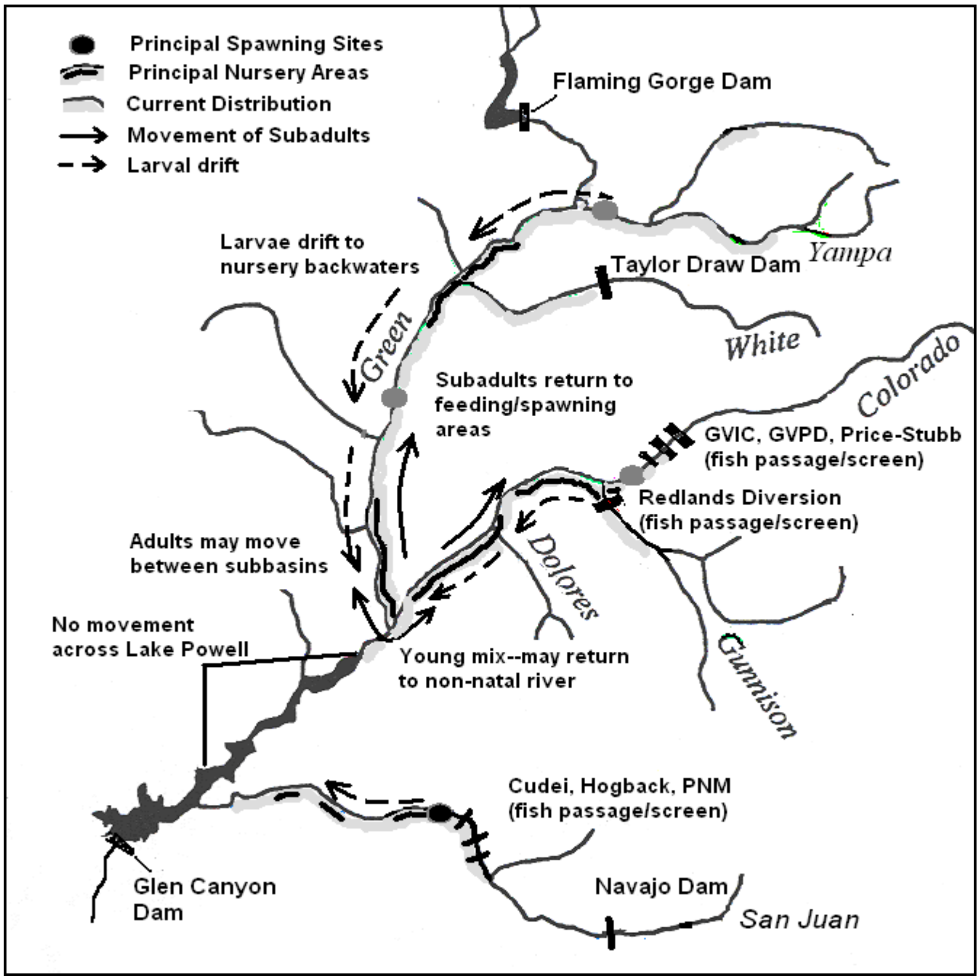

Figure 18. Distribution of Colorado Pikeminnow populations in the Upper Colorado River Basin (shaded areas) with arrows showing larval drift to nursery backwaters, mixing of young at the confluence, movement of adults between subbasins, and return of individuals as subadults to upstream feeding and spawning areas. Dams and diversions that are barriers to fish movement and have been retrofitted with fish passage and screens to minimize entrainment in canals are identified.

Table 10 presents the annual transition probabilities (i.e., Ψ, probabilities of movement to a different reach between years) for average-size Colorado Pikeminnow (500.4 mm TL) captured in the Green River basin, 2000-2003. River reaches are as follows: Yampa River (rkm 192 to rkm 74), White River rkm 167.4 to rkm 0), middle Green River (rkm 539.4 to rkm 396.1), Desolation-Gray Canyon (Green River, rkm 395.9 to rkm 206.1), and lower Green River (rkm 193.2 to rkm 0). Table 6 from Bestgen et al. 2007).

During 1991–2010, there were 54 documented inter-subbasin movements of PIT-tagged Colorado Pikeminnow, including 27 movements from the upper Colorado River subbasin to the Green River subbasin and 27 movements from the Green River subbasin to the upper Colorado River subbasin (Tables 11 and 12; Osmundson and White 2013). Not knowing when movements occurred, length of fish when they moved could only be estimated when captures were 1 year or less apart. From these captures, lengths of migrants ranged from 301 to 615 mm TL. The rate of detected movements from the Green River subbasin to the upper Colorado River subbasin over the 19 years averaged 1.3 per year. In the upper Colorado River subbasin, annual probability of capture of all Colorado Pikeminnow averaged 0.20, suggesting movements from the Green River into the upper Colorado River have averaged 6.5 fish per year. This level of inter-subbasin exchange does not include young fish that are too small to PIT tag that may mix at the confluence of the Green and Colorado rivers and recruit into the non-natal population.

Simple coupled logistics models have been used to show that patches (i.e., populations) with an annual exchange rate of up to about 10% of individuals tend to behave independently; whereas, an exchange of > 10% is likely to affect recruitment, age structure, and survival that may provide an important stabilizing role to populations (Hastings 1993). For Colorado Pikeminnow populations in the Green and upper Colorado River subbasins, the level of exchange between subbasins is < 10% and does not appear to affect the demographic characteristics of either population (as indicated by independent population changes, see Figure 18). However, this level of exchange far exceeds the genetic standard of one migrant per generation that generally ensures genetic panmixia (Mills and Allendorf 1996).

Although Colorado Pikeminnow have not been documented moving between the San Juan River and the Upper Colorado River, razorback sucker (*Xyrauchen texanus*) that were PIT tagged in the San Juan River have been recaptured in the Upper Colorado River. Durst and Francis (2016) documented four razorback sucker individuals originally stocked in the San Juan River, New Mexico, subsequently recaptured in the Colorado and Green rivers, Utah. Each fish moved >550 km between stocking and recapture locations. The time between detections was 171–1,519 days. These movements included ‡210 km through Lake Powell.

Table 10. Annual transition probabilities (i.e., Ψ, probabilities of movement to a different reach between years) for average-size Colorado Pikeminnow (500.4 mm TL) captured in the Green River basin, 2000-2003. River reaches are as follows: Yampa River (rkm 192 to rkm 74), White River rkm 167.4 to rkm 0), middle Green River (rkm 539.4 to rkm 396.1), Desolation-Gray Canyon (Green River, rkm 395.9 to rkm 206.1), and lower Green River (rkm 193.2 to rkm 0). Table 6 from Bestgen et al. 2007).

Reach shift	ψ	95% CI
White to Yampa	0.007	0.001–0.055
White to middle Green	0.048	0.022–0.102
White to Desolation–Gray	0.080	0.043–0.144
White to lower Green	0.003	0.000–0.067
Yampa to White	0	
Yampa to middle Green	0.036	0.009–0.135
Yampa to Desolation–Gray	0.018	0.003–0.122
Yampa to lower Green	0	
Middle Green to White	0.022	0.011–0.045
Middle Green to Yampa	0.018	0.007–0.045
Middle Green to Desolation–Gray	0.045	0.024–0.081
Middle Green to lower Green	0.001	0.000–0.115
Desolation–Gray to White	0.032	0.010–0.099
Desolation–Gray to Yampa	0	
Desolation–Gray to middle Green	0.078	0.031–0.186
Desolation–Gray to lower Green	0.041	0.012–0.131
Lower Green to White	0	
Lower Green to Yampa	0	
Lower Green to middle Green	0	
Lower Green to Desolation–Gray	0.121	0.048–0.274

Table 11. Annual (1991-2005) transition probabilities for the Colorado Pikeminnow 500 mm TL, moving from one study reach of the Upper Colorado River to the other as estimated by the top ranked model. Table 4 from Osmundson and White 2009.

Start year	End Year	Movement		
		From lower to upper reach	From upper to lower reach	Net movement to upper reach
1991	1992	0.0000	0.0000	0.0000
1992	1993	0.2431	0.0000	0.2431
1993	1994	0.2320	0.0000	0.2320
1994	1995	0.1990[1]	0.0000[1]	0.1990[1]
1995	1996	0.1990[1]	0.0000[1]	0.1990[1]
1996	1997	0.1990[1]	0.0000[1]	0.1990[1]
1997	1998	0.1990[1]	0.0000[1]	0.1990[1]
1998	1999	0.0000	0.0000	0.0000
1999	2000	0.0461	0.1580	-0.1119
2000	2001	0.0000[2]	0.0900[2]	-0.0900[2]
2001	2002	0.0000[2]	0.0900[2]	-0.0900[2]
2002	2003	0.0000[2]	0.0900[2]	-0.0900[2]
2003	2004	0.0563	0.0000	0.0563
2004	2005	0.3046	0.0000	0.3046

[1] Average per year calculated from single value for period 1994-1998; no capture data available for these individual un-sampled years; annual estimates for these years might be higher or lower than average value provided if capture data were available.
[2] Average per year calculated from single value for period 1998-2000.

Table 12. Total number of Colorado Pikeminnow captures in upper basin rivers since use of PIT tags began, 1990-2010. Values represent the number of captures, including recaptures, and not individual fish. Fish captured more than once on the same day are counted as only one capture. PIT tags were used in 1990 in the Colorado River but not in other rivers. Captures in other rivers in 1990, without use of PIT tags, are not shown. Captures recorded for the Gunnison River include fish above and below the Redlands Diversion Dam (RM 2.2). Capture records for 2004 and 2005 in the Colorado River do not include the capture of recently stocked fish. Table from Osmundson and White (2014).

Year	CO[1]	GU[2]	DO[3]	GR[4]	WH[5]	YA[6]	DU[7]	PR[8]	SR[9]	LS[10]	TOTAL
1990	23	0	0	0	0	0	0	0	0	0	23
1991	118	3	3	82	22	72	0	0	0	0	300
1992	133	4	0	142	19	53	0	0	0	0	351
1993	209	10	0	114	72	42	7	0	0	0	454
1994	209	42	0	208	34	19	0	0	0	0	512
1995	117	20	0	442	38	21	0	1	0	3	642
1996	124	16	0	299	42	42	2	6	0	0	531
1997	133	22	0	327	60	23	9	11	0	0	585
1998	358	37	0	493	43	57	3	1	6	0	998
1999	266	15	0	356	72	63	25	2	0	0	799
2000	254	11	0	867	326	141	23	0	0	0	1,622
2001	39	3	0	952	239	235	0	0	0	0	1,468
2002	0	7	0	504	184	50	0	0	0	0	745
2003	187	7	0	388	121	67	0	0	0	0	770
2004	199	23	0	144	0	75	0	0	0	0	441
2005	363	8	0	157	0	56	0	0	0	0	584
2006	0	10	0	799	106	62	7	0	0	0	984
2007	3	23	0	720	136	52	0	0	1	0	935
2008	179	10	0	507	67	33	0	0	0	0	796
2009	186	13	0	229	11	119	0	0	0	0	558
2010	184	14	0	245	3	118	0	0	0	0	564
Total	3,284	298	3	7,975	1,595	1,400	76	21	7	3	14,659

1 Colorado River
2 Gunnison River
3 Dolores River
4 Green River
5 White River
6 Yampa River
7 Duchesne River
8 Price River
9 San Rafael River
10 Little Snake River

9.0 Larval Drift and Transport

9.1 Larval Drift and Transport

Abundance of Colorado pikeminnow larvae in drift net samples varied widely within and among years (Figure 19). More than 1,000 larvae were captured in each of 1990, 2000, and 2012 in the Yampa River, all lower flow years and only 49 were captured in 1995, a high flow year. Annual captures of larvae in the lower Green River samples varied from 16 to 175; relatively few compared to Yampa River samples.

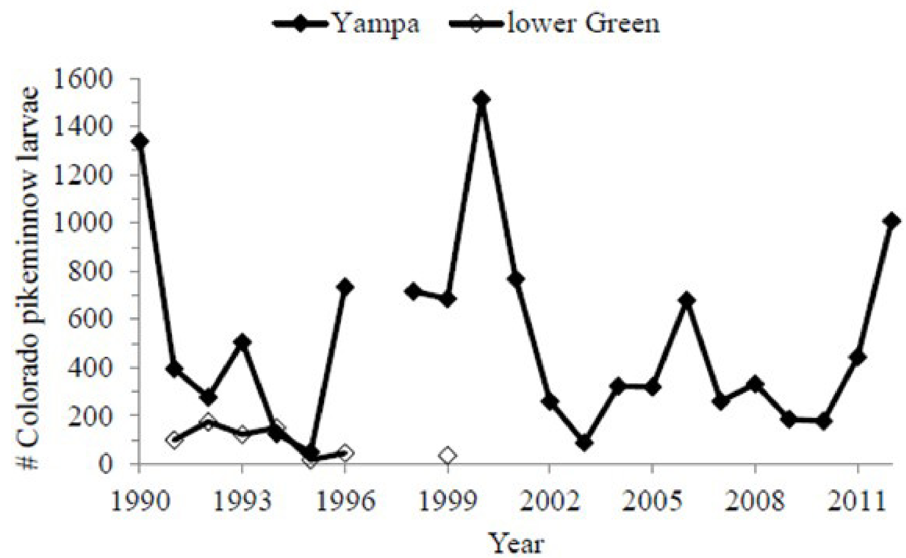

Figure 19. Number of Colorado Pikeminnow larvae captured in drift nets by year, lower Yampa River, Colorado, and lower Green River, Utah. Figure 7 from Bestgen and Hill (2015).

Colorado pikeminnow adults migrate in late spring and summer to spawning areas in the upper Colorado River basin when spring flows are declining and water temperatures are increasing (Tyus 1990, 1991; Bestgen et al. 1998; Irving and Modde 2000; McAda 2003). In the Green River subbasin, Colorado pikeminnow move long distances, sometimes > 800 RK round-trip to two main spawning areas in Gray Canyon of the Green River and Yampa Canyon in Dinosaur National Monument (Figure 20). The Yampa Canyon spawning population has been monitored for many years and production of larvae from that area is variable and low in low flow years, but continues at a high level (Bestgen and Hill 2015).

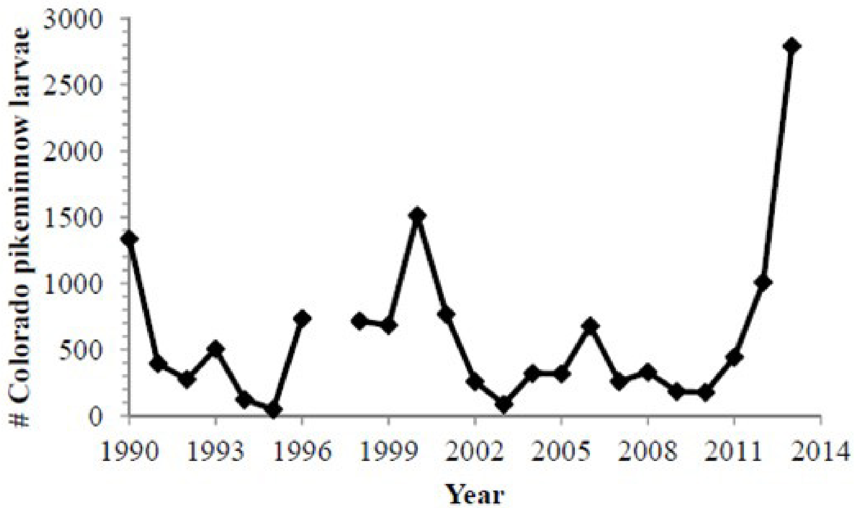

Figure 20. Number of Colorado Pikeminnow larvae captured from 1990 to 2013 (no sampling in 1997, includes specimens from all diel samples, 2014 sample identification is underway) in the lower Yampa River, Colorado, during summer in drift nets. Figure 3 from Bestgen and Jones (2015).

9.2 Relationship of Flow to Larval Transport

The relationship of mean July-August flows for the Yampa River during summer to the Colorado pikeminnow larvae transport abundance index was positive (the relationship with very high 1995, 1997, and 2011 flow peak years excluded [not depicted in Figure 21) was $r^2 = 0.64$). Yampa River mean July-August base flow levels < 14.2 m3/sec (< 500 ft3/sec) often resulted in low production and downstream transport of Colorado pikeminnow larvae. In contrast, mean base flows > 14.2 m3/sec (500 ft3/sec) generally resulted in higher transport abundance of Colorado pikeminnow larvae (Bestgen and Hill 2015).

Annual transport abundances for Colorado pikeminnow larvae in the lower Green River were relatively stable up to peak discharges of about 700 m3/sec (24,700 ft3/sec) but declined at flow levels greater than that (Figure 22). Similarly, transport abundance remained high at summer base flow levels up to about 100 m3/sec (3,530 ft3/sec), but declined at flow levels greater than that; decreasing sampling efficiency in higher flow years may have been an issue (Bestgen and Hill 2015).

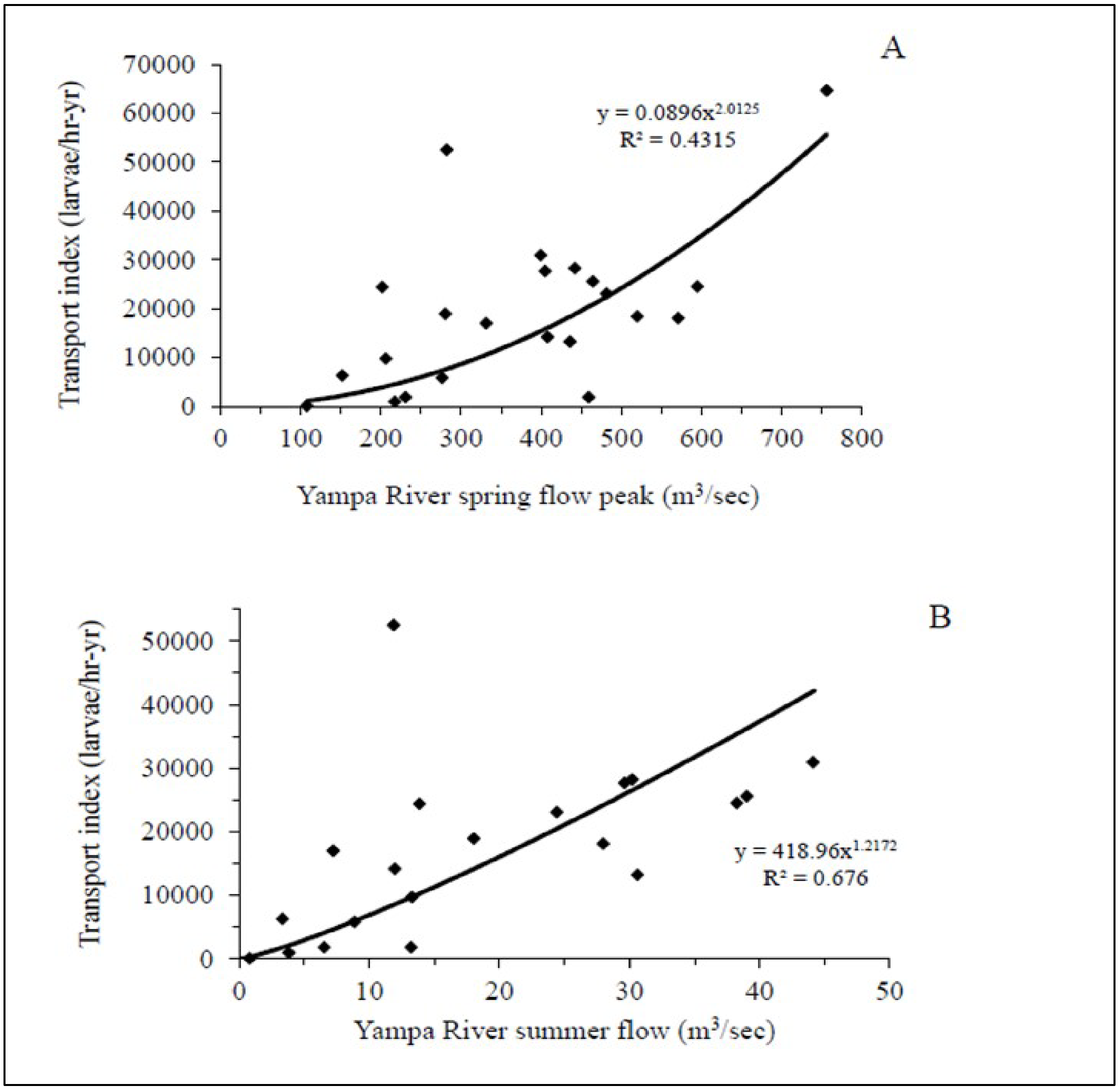

Figure 21. Colorado Pikeminnow larvae transport index as a function of spring peak flow (panel A) and mean July-August summer base flow (panel B), lower Yampa River, Colorado, 1990-2012 (no sampling in 1997). Transport abundance was estimated by dividing the number of larvae captured in three dawn nearshore drift net samples adjusted to an hourly rate by the estimated proportion of total discharge that was sampled. Figure 10 from Bestgen and Hill (2015).

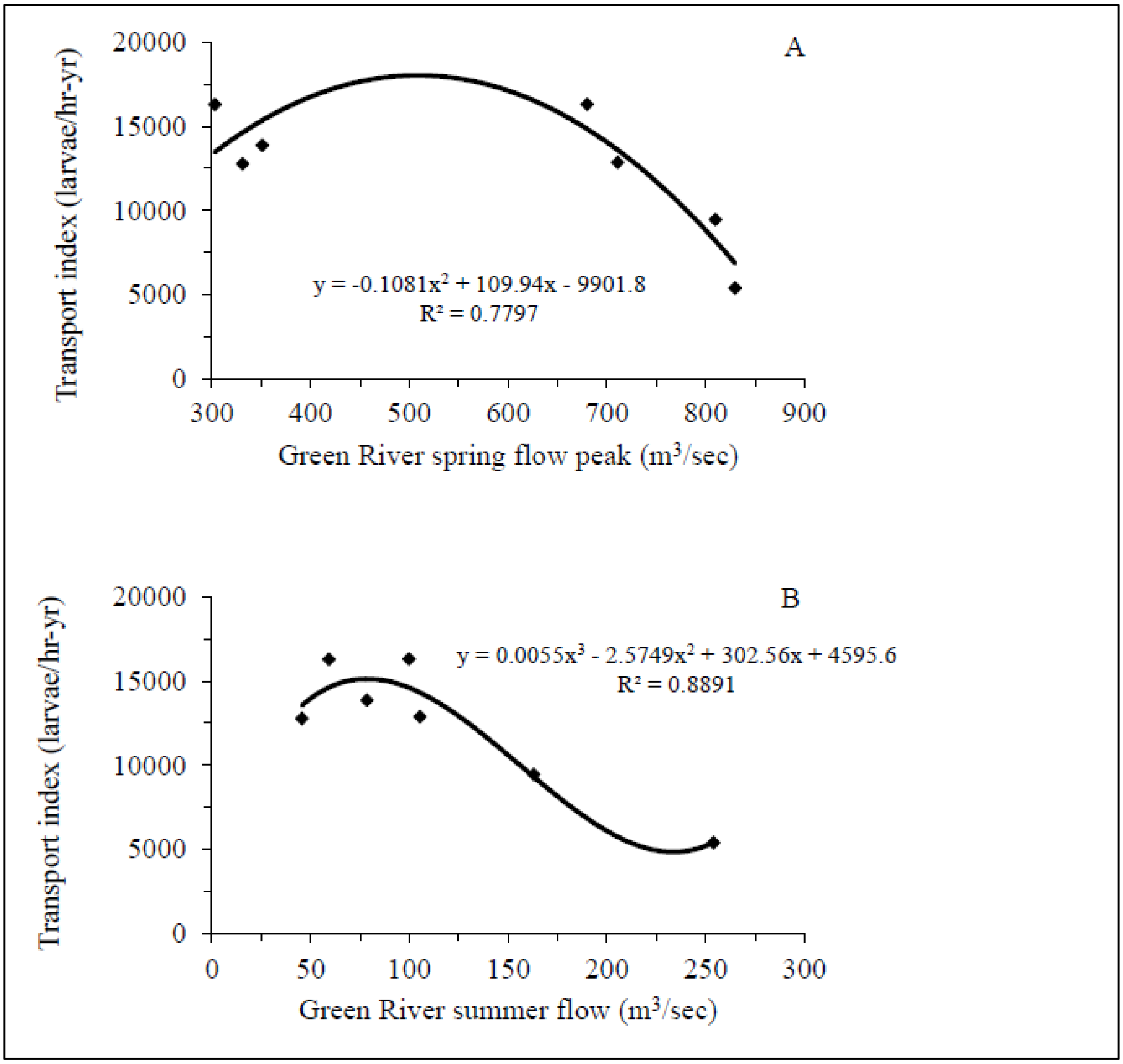

Figure 22. Colorado Pikeminnow larvae transport index as a function of spring peak flow (panel A) and mean July-August summer base flow (panel B), lower Green River, Utah, 1991-1996, 1999. Transport abundance was estimated by dividing the number of larvae captured in three dawn nearshore drift net samples adjusted to an hourly rate by the estimated proportion of total discharge that was sampled. Figure 11 from Bestgen and Hill (2015).

10.0 Age-0 Density and Backwater Availability

10.1 Age-0 Density

In the middle Green River, density of age-0 Colorado pikeminnow was variable but showed a dome-shaped relationship with mean August-September summer baseflow (Figure 23). Densities were highest at intermediate flow levels of 1,700-3,000 ft3/sec, but were much lower at flows < about 1,700 ft3/sec and > about 3,000 ft3/sec; flows > 2,500 ft3/sec produced only a single year with above average age-0 pikeminnow abundance. Dashed lines indicate the intermediate range of flows that encompasses most of the years when densities of age-0 Colorado pikeminnow were highest, recognizing that pikeminnow were not abundant every year. For example, in that intermediate flow range, age-0 Colorado pikeminnow densities were > 0.51/10 m2 of habitat seined, the mean density over 34 years of sampling, in 10 of 16 years (63% of the time). In comparison, during lower flow years, pikeminnow densities were that high in only 2 of 13 years (15% of the time), and in the five years when flows were higher, pikeminnow density never exceeded the mean level. Thus, the intermediate flow range encompassed by the dashed line included all but two of the years when pikeminnow abundance was greater than the overall mean of 0.51 fish/10 m2. The two higher density years in the lower flow range were 1988 and 1990, historical records of importance to be sure, but were from the pre-1994 period when pikeminnow were much more abundant (Bestgen and Hill 2015).

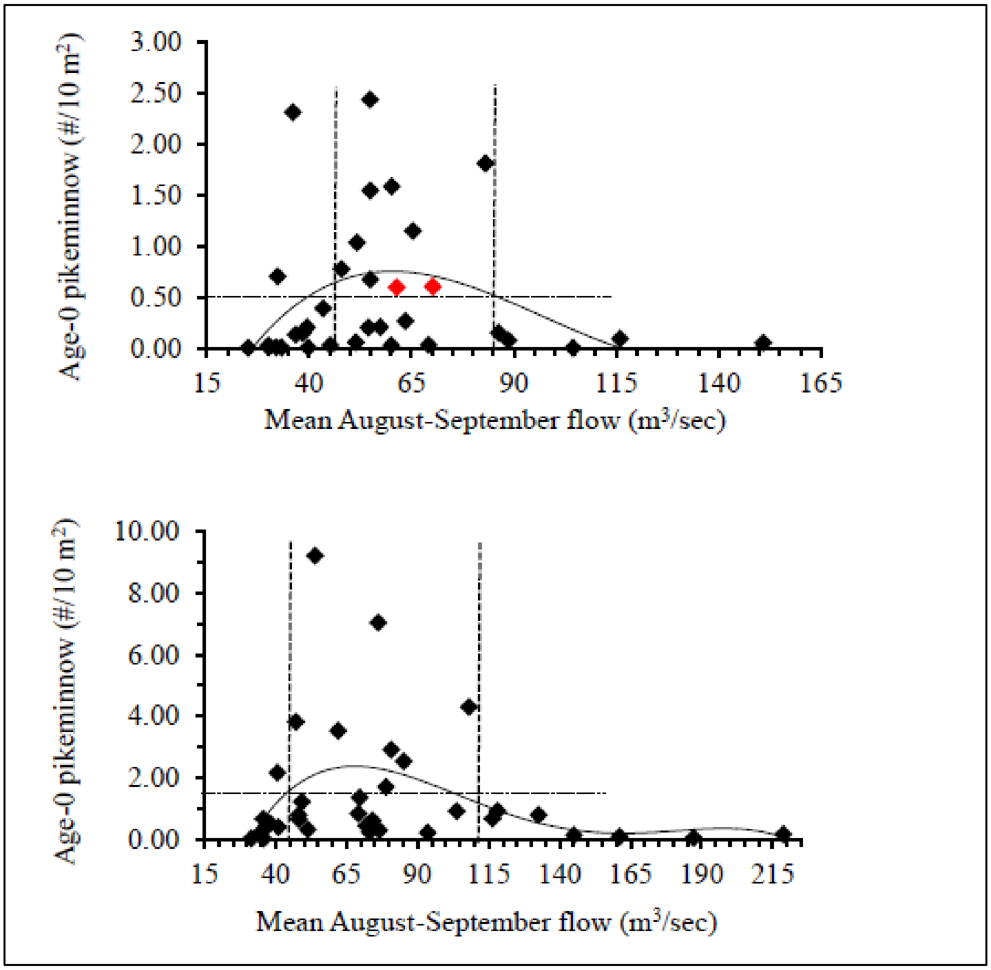

Figure 23. Mean annual density of age-0 Colorado pikeminnow captured in backwaters of the middle (upper panel) and lower (lower panel) Green River as a function of mean August-September flow, 1979-2012. Density is number of pikeminnow captured in area of backwaters swept by a seine. The middle Green River 2009 and 2010 data are red triangles. Dashed vertical lines encompass the flow ranges in each reach when the proportion of above average recruitment years is highest, and the horizontal dotted line is the mean density for the period of record. Polynomial regression relationships illustrate the dome-shaped nature of the recruitment relationship at intermediate flow levels. Green River flows were measured at the Jensen, Utah gauge (09261000) for the middle Green River reach and at the Green River, Utah gauge (09315000) for the lower Green River reach. Figure 18 from Bestgen and Hill (2015).

10.2 Backwater Availability

Reanalysis of Pucherelli et al. (1990) showed backwater number/km was highest in Island Park, but was also high in Ouray and Jensen reaches (Figure 24). In general, backwater number declined at the highest flow of 142 m3/sec (5,000 ft3/sec), but within the lower range of flows from 37-71 m3/sec (1,300-2,500 ft3/sec), backwater numbers were essentially stable; only the relatively short Sand Wash reach showed an increase in backwater number with flow level. The Mineral Bottom reach in the lower Green River had the lowest number of backwaters/km of any Green River reach and that number was essentially stable over the limited range of flows sampled.

In the middle Green River, backwater area was highest in the Ouray reach, followed by Sand Wash, Island Park, and Jensen, over the range of flows that excluded the highest flow measured. Mineral Bottom also had the lowest area of backwater habitat by a substantial margin. In general, backwater area declined at the highest flow level sampled, but at Ouray and Sand Wash, area was stable and high at the lower range of flows (37-71 m3/sec; 1,300-2,500 ft3/sec), and declined over the range of flows sampled at Island Park and Jensen. Backwater area at Mineral Bottom was relatively stable and very low. In general, backwater number and area/km were highest in the Jensen, Ouray, and Sand Wash reaches at flows up to 71 m3/sec (2,500 ft3/sec). Similarly, in the lower Green River, backwater habitat area was stable, over the limited range of flow levels examined (Bestgen and Hill 2015).

In general, Day et al. (1999) and Trammell and Chart (1999) found the middle Green River supported many more backwaters in the same length of river than the lower Green River (mean/year = 68 and 25 respectively, Figure 25). Mean backwater number was similar in 1992-1996 in the middle (4.25/RK) and lower Green River (1.6/RK) compared to the number in Pucherelli et al. (1990) in 1987, but backwater number was much higher in the middle Green River. Similarly, in 1992-1996, total backwater area was on average 4.5 times greater in the middle Green River than the lower Green River, because of greater backwater number and larger mean area (626 vs 454 m2, respectively). However, because age-0 Colorado pikeminnow density in backwaters was higher in the lower Green River than the middle Green River (means = 1.25 vs. 0.25/10 m2, respectively), mean estimated pikeminnow abundance for the reach (backwater area x pikeminnow density) was similar in the middle and lower Green River over the 1992-1996 study period (1199 and 1158, respectively, per 16 RK reach per year) (Bestgen and Hill 2015).

The surface area of backwater habitats by year and geomorphic reach is shown for the San Juan River, as measured during fall base flow (Figure 26; ERI 2014).

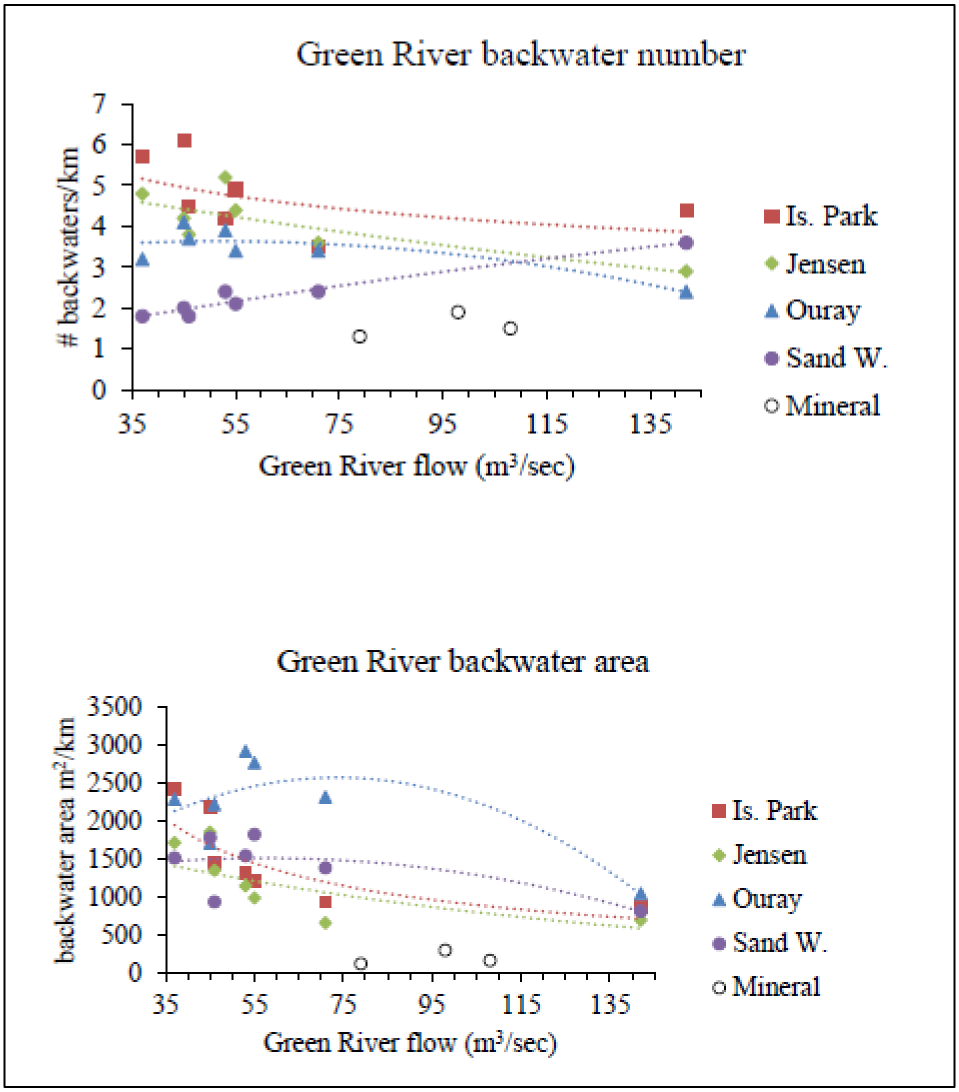

Figure 24. Green River backwater number (upper panel) and area (lower panel) per river km in Island Park, Jensen, Ouray, Sand Wash (all in middle Green River reach), and Mineral Bottom (lower Green River) reaches, 1987. Mineral Bottom data not fit with a line because only three occasions were measured. Green River flows were measured at the Jensen, Utah gauge (09261000) for all but the Mineral Bottom site, which were measured at the Green River, Utah gauge (09315000). Figure 22 from Bestgen and Hill (2015).

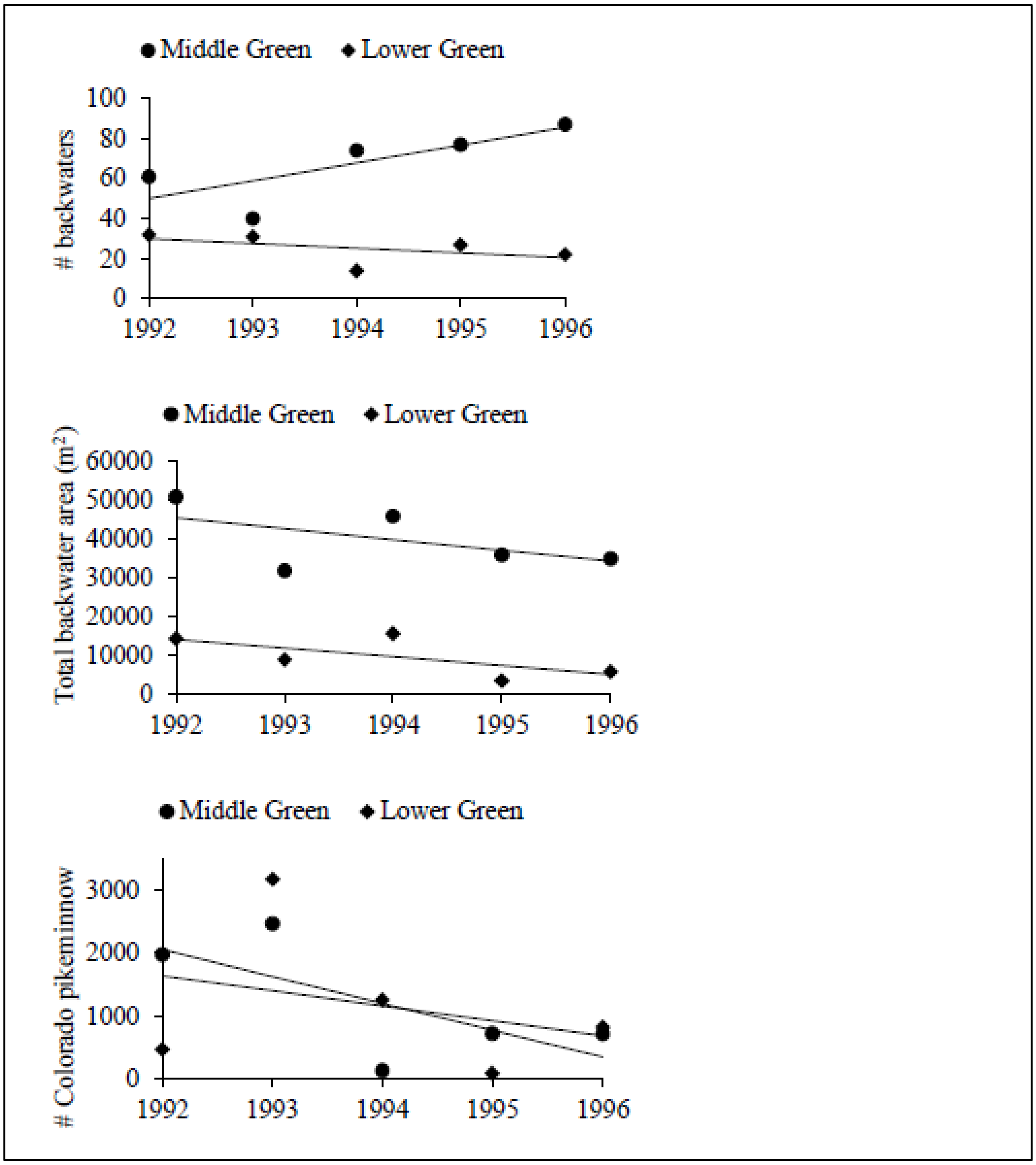

Figure 25. Number of backwaters (upper panel), total backwater area (middle panel), and estimated age-0 Colorado pikeminnow density (lower panel) in 16 river km reaches of the middle Green River (Ouray National Wildlife Refuge, RK 421.6-405.5), and the lower Green River (Mineral Bottom area, RK 91.7-75.7), Utah, 1992-1996. Similarity in Colorado pikeminnow abundance is due to higher density in the lower Green River in spite of lower number and area of backwaters. Figure 23 from Bestgen and Hill (2015).

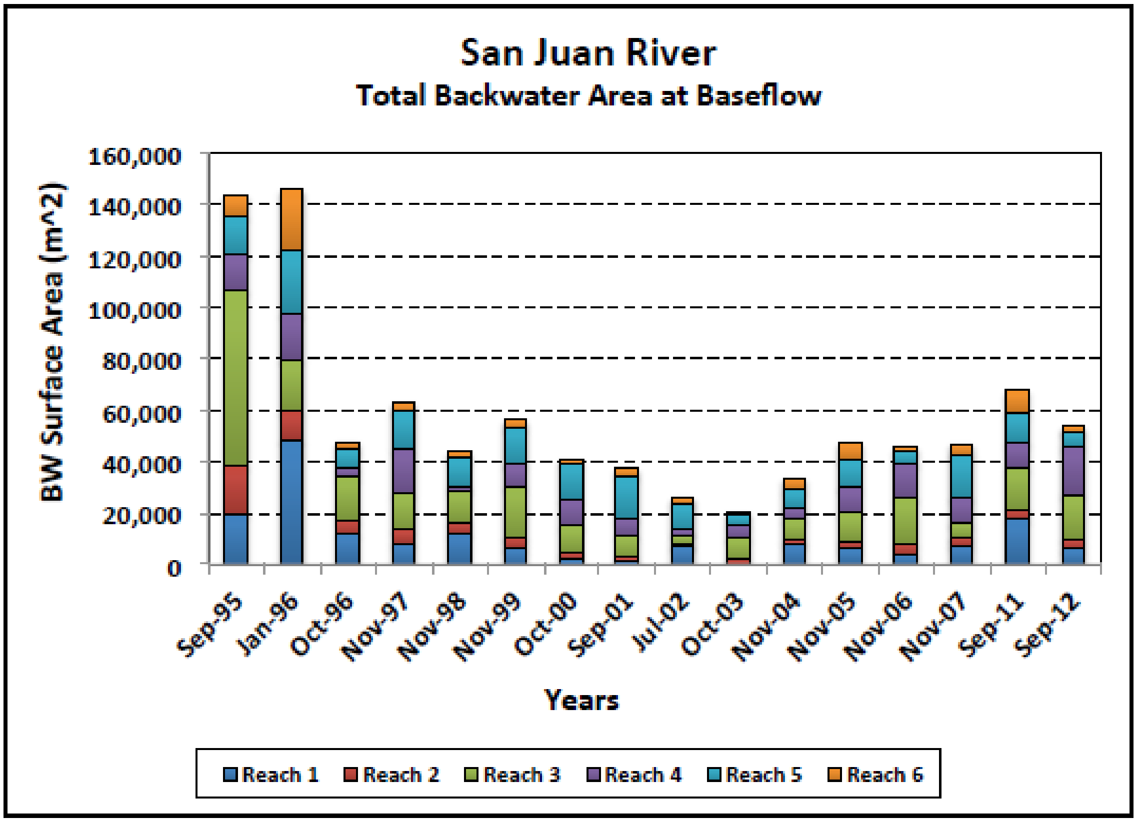

Figure 26. Surface area of backwater habitats by year and geomorphic reach for the San Juan River, as measured during fall base flow. Figure from ERI (2014).

11.0 Stocking

11.1 Green River Subbasin

About 32 000 fingerlings were stocked in Kenney Reservoir of the White River in April 1989; unknown number stocked in 1988.

11.2 Upper Colorado River Subbasin

About 1,500 age VI fish were stocked in the Colorado River near Moab, UT in April 1980, and 5,084 hatchery-reared fish were stocked in the Gunnison and Colorado rivers in 2003 and 2004 (Table 13). None of 2,069 stocked in 2003 were recaptured, and 72 of 3,015 stocked in 2004 were recaptured to 2008. Estimated survival rate of stocked fish after 4 years was 0.3% (Osmundson and White 2014).

Table 13. Colorado Pikeminnow stocking information for the Colorado and Gunnison rivers, 2003 and 2004. Abbreviations: RM = river mile; FWS = U.S. Fish and Wildlife Service; CPW = Colorado Parks and Wildlife. Table from Osmundson and White (2014).

Stocking Date	Agency	River	RM location	Number stocked	Mean length (mm)	Length range (mm)
2003						
Apr 14	FWS	Colorado	167.7	12	120	100–140
Oct 10	FWS	Gunnison	57.1	1,048	242	116–311
Nov 06	FWS	Colorado	216.6	1,001	222	152–350
Total				**2,069**		
2004						
May 18	CPW	Colorado	240.7	1,164	184	134–292
Jun 01	CPW	Gunnison	57.0	1,200	217	142–270
Sep 15	CPW	Colorado	240.7	651	204	150–235
Total				**3,015**		

11.3 San Juan River Subbasin

Over 2.7 million fish were stocked in the San Juan River from 1996 to 2006, (Ryden 2003b, 2004). Between 175,928 and 475,970 age-0 fish were stocked annually in November during 2002 to 2014 (total: 4,366,328; Table 14). Between 353 and 12,661 age-1+ fish were stocked annually in November during 2002 to 2011 (total: 40,116; Table 15).

The numbers recaptured by year are shown in Tables 14 and 15. Estimated number of age 2+ fish (> 150 mm TL) was 4,666 in 2009 and over 5,400 in 2010.

Table 14. Number of Colorado Pikeminnow stocked at age 0 from 2002-2013 and recaptured from 2003-2014 in the San Juan River. The number of recaptures is based only on individuals large enough to be implanted with a PIT tag during their TAG record (≥ 150 mm TL). The total number of individuals recaptured may be less than the sum of the number of individuals recaptured by year because some individuals are recaptured in multiple years. The number of individuals from a particular stocking class can be examined looking across rows. The number of individuals captured by year from different stocking classes can be examined looking down columns. Note that the total number of Pikeminnow captured in any year includes those fish that could not be assigned to a particular year class. The 2010 year class Pikeminnow stocked in May 2011 without PIT tags were age 1 fish that should have been stocked in 2010 as age 0. For the purpose of this report, all Pikeminnow stocked into the San Juan River without PIT tags are considered age 0 (From Durst 2015, Table 2). A total of 393,442 age-0 fish were stocked Nov 6, 2014 (Furr 2015).

				Individuals captured by year											
Year stocked	Year class	Number stocked	Total captured	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
	UNKNOWN		112	3	1	2	15	7	4	12	19	27	19	22	21
2002	2002	210,418	211	73	132	11	0	1	0	0	0	0	0	1	0
2003	2003	175,928	446	-	190	233	33	2	0	0	0	0	0	0	0
2004	2004	280,000	341	-	-	155	183	22	5	4	2	0	2	1	1
2005	2005	302,270	547	-	-	-	393	138	37	11	1	4	1	0	3
2006	2006	313,854	507	-	-	-	-	270	224	80	7	3	1	0	4
2007	2007	475,970	872	-	-	-	-	1	395	476	76	20	6	5	3
2008	2008	270,234	2,108	-	-	-	-	-	-	899	1,124	353	8	3	2
2009	2009	468,000	1,949	-	-	-	-	-	-	-	1,042	962	48	6	3
2011	2010	214,720	1,033	-	-	-	-	-	-	-	-	555	456	74	7
2011	2011	426,588	1,032	-	-	-	-	-	-	-	-	-	667	371	47
2012	2012	395,640	598	-	-	-	-	-	-	-	-	-	-	420	200
2013	2013	439,264	197	-	-	-	-	-	-	-	-	-	-	-	197
Total individuals captured				76	323	401	624	441	665	1,482	2,271	1,924	1,212	903	488

Table 15. Number of Colorado Pikeminnow stocked as age 1+ and recaptured by year, 2003-2014 in the San Juan River. The total number of individuals recaptured may be less than the sum of the number of individuals recaptured by year because some individuals are recaptured in multiple years. The number of individuals from a particular stocking class can be examined looking across rows. The number of individuals captured by year from different stocking classes can be examined looking across columns. Note that the relatively small number of age 1+ Colorado Pikeminnow stocked in 2010 was due to the detection of largemouth bass virus at SNARCC resulting in a quarantine of fish held at that hatchery. Those fish held over from 2010 were stocked in 2011. Also, 2011 was the last year that age 1+ Colorado Pikeminnow were stocked into the San Juan River (From Durst 2015, Table 3).

			Individuals captured by year											
Year stocked	Number stocked	Total captured	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2003	1,002	3	3	0	0	0	0	0	0	0	0	0	0	0
2004	1,217	79	-	66	13	1	0	0	0	0	0	0	0	0
2005	4,119	89	-	-	84	5	0	0	0	0	0	0	0	0
2006	12,661	357	-	-	-	294	53	6	6	2	2	1	1	2
2007	3,250	233	-	-	-	-	141	79	16	1	3	0	0	1
2008	4,848	628	-	-	-	-	-	203	439	16	2	1	0	1
2009	8,942	565	-	-	-	-	-	-	470	108	14	4	1	3
2010	353	43	-	-	-	-	-	-	-	35	8	0	3	0
2011	3,724	295	-	-	-	-	-	-	-	-	269	25	1	1
Total individuals captured			11	68	99	300	194	288	931	162	298	31	6	8

12.0 Predation and Competition

Predation and competition by non-native fishes have been recognized as threats to the Colorado Pikeminnow since the 1950s (Miller 1961), but the impact of predation on survival of Colorado Pikeminnow has not been isolated from other causes of mortality. At least 67 species of non-native fishes have been introduced into the Colorado River System during the last 100 years, many of which prey upon and compete with the 35 species that are native to the System (Valdez and Muth 2005). The range in sizes of non-native fishes that prey on and compete with Colorado Pikeminnow encompasses the entire life history of the species and there is no apparent refuge size where predation and competition is reduced.

12.1 Green River Subbasin

Northern pike (*Esox lucius*), smallmouth bass, and channel catfish (*Ictalurus punctatus*) have also been identified as the principal predators of subadult and adult Colorado Pikeminnow in the last two decades. Northern pike escaped from Elkhead Reservoir into the Yampa River in the early 1980s (Tyus and Beard 1990) and established a reproducing population by the 1990s that expanded in the Yampa River and into the middle Green River (Tyus and Beard 1990; Hawkins and Nesler 1991; Nesler 1995) where they pose a competitive and predatory threat to native fishes of all sizes (Wick et al. 1985; Tyus and Karp 1989; Tyus and Beard 1990; Bestgen et al. 2007a, 2007b).

Smallmouth bass also escaped from Elkhead Reservoir into the Yampa River in the early 1990s and became abundant during low stream flows in 2001-2003; the species is prolific, highly predaceous at all life stages, and threatens small and medium-size native fishes. Adult channel catfish and northern pike often use the same habitats as subadult and adult Pikeminnow, where these species compete for food and prey on each other, especially during periods of limited resource availability (Wick et al. 1985; Tyus and Karp 1989; Tyus and Beard 1990; Nesler 1995; Bestgen et al. 2007a, 2007b).

Channel catfish were first introduced into the Upper Colorado River Basin in 1892 (Tyus and Nikirk 1990) and are now common to abundant (Tyus et al. 1982; Nelson et al. 1995). The species is one of the most prolific predators and competitors in the upper basin due largely to resource overlap and tolerance to poor water quality conditions during droughts and in marginal habitats (Hawkins and Nesler 1991; Lentsch et al. 1996; Tyus and Saunders 1996). Colorado Pikeminnow also prey on non-native fishes, but the spines of channel catfish may lodge in the throats of Pikeminnow possibly leading to their death (McAda 1980; Pimental et al. 1985).

Non-native fish control in the upper basin has focused on five fish taxa; northern pike, smallmouth bass, channel catfish, centrarchids (sunfishes including largemouth bass, green sunfish, crappie), and cyprinids (minnows including red shiner, fathead minnow [*Pimephales promelas*], sand shiner [*Notropis stramineus*]) (Martinez et al. 2011).

Efforts to control northern pike in the Yampa River began in 1999 (Hawkins et al. 2005) when fish taken from the river were relocated to nearby isolated ponds or reservoirs accessible to anglers and in conformance with the Procedures for Stocking Nonnative Fish Species in the Upper Colorado River Basin (USFWS 1996). Annual removal of northern pike in three reaches of the Yampa River (Juniper, Maybell, and Lily Park) has resulted in a net decline in numbers of pike captured (Wright 2010) which effectively reduces the number of large predators on Pikeminnow as well as other native fishes. While the numbers of northern pike in the middle and lower Yampa River have been reduced, northern pike in the upper Yampa River persist in large numbers in reservoirs and complex floodplains, but control and translocation efforts continue to suppress this population to reduce downstream dispersal (Webber 2010). In the Yampa River (RM 50.2 and 134.2), annual estimated densities of northern pike (> 300 mm TL), a functionally similar predator to Colorado Pikeminnow, reach a maximum density of 18.9 fish/mi in 2012 (Battige 2012).

Northern pike have also been effectively removed from the middle Green River starting in 2001 (Monroe and Hedrick 2008), and most pike in the middle Green River are immigrants from the Yampa River; there appears to be little or no local reproduction by pike in the Green River. Northern pike are uncommon in the Upper Colorado River subbasin and no specific removal program is in place for this species.

Control of smallmouth bass began in the Yampa River in 2004 following a dramatic increase in the population. Smallmouth bass were rare in Yampa Canyon in 1997, but increased to 18% of the adult fish composition in 2004, concurrent with a decline in native species composition from 84% in 1997 to 45% in 2004 (Haines and Modde 2007). Efforts to control smallmouth bass have had variable success. Control measures are effective at suppressing numbers of bass, except for strong year classes such as 2007 in the middle Green River (Monroe and Hodge 2010) and 2008 in the middle and lower Yampa River (Hawkins et al. 2009, 2010). Similarly, suppression of smallmouth bass numbers has been effective in the Upper Colorado and Gunnison rivers, except during strong year classes such as 2005-2007 (Burdick 2010). Populations of smallmouth bass appear to increase in years of low stream flow and are suppressed in years of high flow, most likely because low flows favor habitat and temperature required for egg production and survival of young. Numbers of smallmouth bass have been reduced in Desolation/Gray Canyon largely because there is little or no local reproduction and the fish are largely immigrants from upstream populations (Badame et al. 2008).

Attempts to mechanically reduce numbers of channel catfish in Desolation/Gray Canyon (Badame et al. 2008; Chart and Lentsch 1999) and Yampa Canyon (Haines and Modde 2007; Fuller 2009) have had limited success and other strategies are being explored. Removal of centrarchids has also been implemented in Upper Colorado River floodplains and nursery backwaters (Burdick 2008), and sources of non-native fish have been identified through stable isotope analysis (Johnson et al. 2008; Whitledge et al. 2006, 2007) and isolated to prevent fish escapement to the river (Martinez et al. 2011).

Simulated effects of cool and warm thermal regimes and hatching date on survival and total length of Colorado pikeminnow larvae hatched from 1 June to 1 August in the Green River, Utah have been done to show the effect of predator density (Figure 27; Bestgen et al. 2006). Frequency distributions of growth rates of Colorado pikeminnow larvae in the Green River, Utah, with and without size-dependent predation by red shiners have also been show (Figure 28), as well as effect on age-0 density (Figure 29).

12.2 Upper Colorado River Subbasin

About 20 non-native fish species occupy the same habitat as the Colorado Pikeminnow in the upper basin. Nursery backwaters and low-velocity shorelines are the areas of highest predation on young Colorado Pikeminnow (Haines and Tyus 1990; Tyus 1991; Holden 1999; McAda 2003; Muth et al. 2000). Predation of young fish limits survival and recruitment (e.g., Muth and Nesler 1993; Bestgen et al. 1997; McAda and Ryel 1999; Valdez et al. 1999; Bestgen et al. 2007a, 2007b). Osmundson (1987) confirmed predation by black bullhead (*Ameiurus melas*), green sunfish (*Lepomis cyanellus*), largemouth bass (*Micropterus salmoides*), and black crappie (*Pomoxis nigromaculatus*) as a significant mortality factor of age-0 Colorado Pikeminnow stocked in riverside ponds along the Upper Colorado River. Adult red shiners (*Cyprinella lutrensis*) were also reported as significant predators of larval native fish in backwaters (Ruppert et al. 1993).

12.3 San Juan River Subbasin

Changes in the composition of the San Juan River's fish community occurred with construction of Navajo Dam and nonnative fish introductions. The historical fish community of the San Juan River was relatively depauperate with only eight species (Sublette et al. 1990), but recent investigations have documented 19 non-native fishes (Ryden 2000). Non-native fishes prey on and compete with the native species, but also provide may be potential a source of prey for Colorado Pikeminnow (Franssen and Durst 2013). The nonnative fishes of greatest concern in the San Juan River are the channel catfish and common carp. An extensive non-native fish control program has been implemented on the San Juan River with the primary target of channel catfish (SJRIP 2009; Davis et al. 2010; Elverud 2010). Mechanical removal has resulted in reduced numbers of large channel catfish (> 525 mm TL) river-wide, but there has been a shift towards smaller fish since 1996 and recolonization from upstream movement (Miller 2006; Franssen et al. 2014). Numbers of common carp have decreased substantially with removal of that species from the system.

Despite predictions that the catch numbers of age 1 and age 2+ Colorado Pikeminnow are associated with the catch rate of predators (i.e., adult channel catfish > 300 mm TL), Franssen and Durst (2013) found no negative effects of adult channel catfish on numbers of Colorado Pikeminnow captured. It is noted that other interactions may be negatively affecting Colorado Pikeminnow in conjunction with the presence of nonnative fishes.

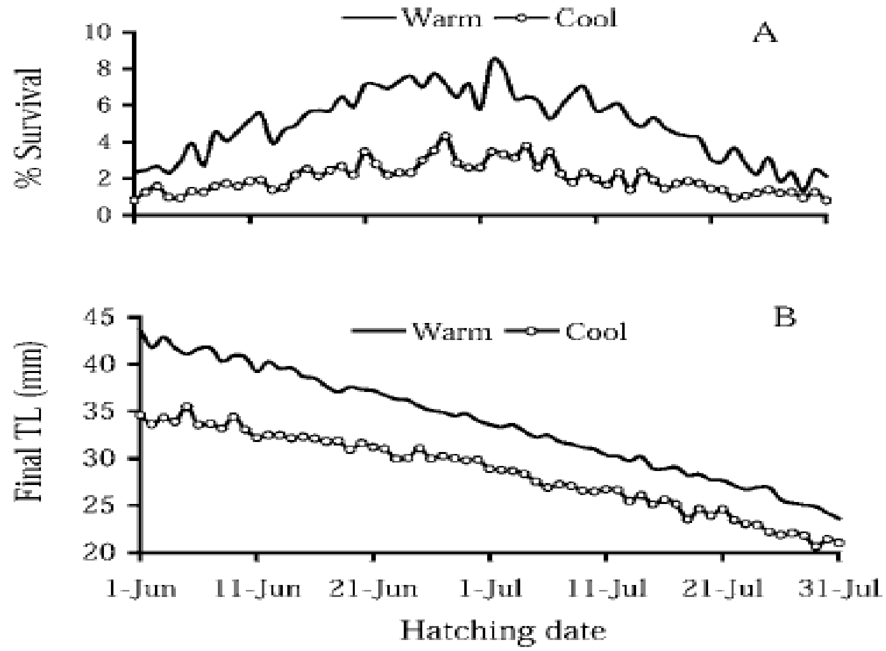

Figure 27. Simulated effects of cool and warm thermal regimes and hatching date on (A) survival and (B) final total length (TL) of Colorado pikeminnow larvae that hatched from 1 June to 1 August in the Green River, Utah. Simulations ended 1 October, and predator density was 6 red shiners/m2 (Fig. 8 from Bestgen et al. 2006).

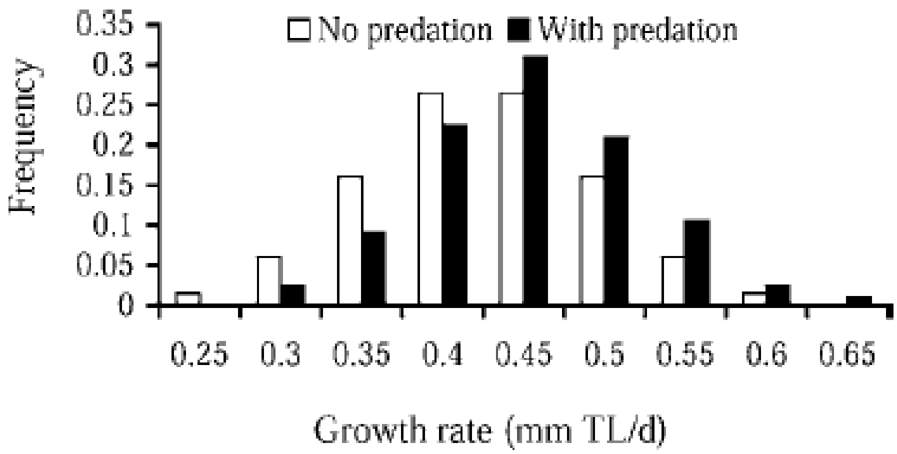

Figure 28. Frequency distributions (means of five simulations) of growth rates of Colorado pikeminnow larvae in the Green River, Utah, with and without size-dependent predation by red shiners, as derived by an individual-based recruitment model. Individuals in both cohorts were assigned a growth rate by random draw from an initial distribution of growth rates that had a mean of 0.4 mm/d (SD ¼ 0.07) (Fig. 10 from Bestgen et al. 2006).

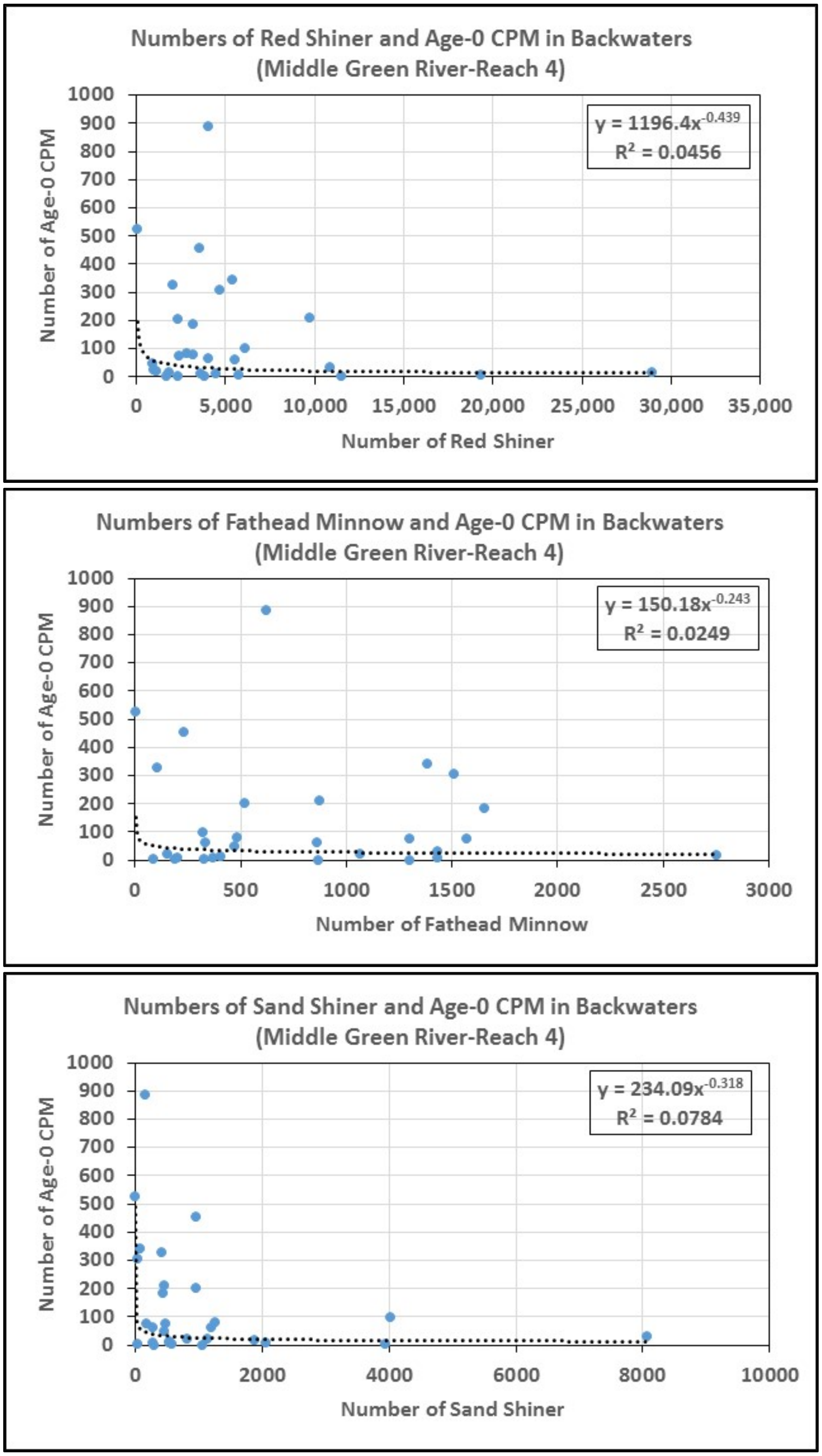

Figure 29. The above figures were created with data from Breen et al. (2015) for numbers of Red Shiner, Fathead Minnow, and Sand Shiner captured in backwaters with Colorado Pikeminnow.

13.0 Habitat

13.1 River Gradients

Spawning sites of Colorado Pikeminnow in the Green River, Upper Colorado River, and Yampa River are located in river reaches with gradients of 5.3 and 11.3, 7.7, and 8.2 ft/mi, respectively; whereas nursery areas in the Green River and Upper Colorado River occur in reaches with lower gradients of 1.6 and 3.0, and 2.3 ft/mi, respectively (Figure 30). The gradients of the San Juan River for Navajo Dam to Animas River, Animas River to Bluff, and Bluff to Clay Hills are 13.2, 7.4, and 8.3 ft/mi, respectively, which are within the range of gradients used for spawning, but higher than gradients used as nursery areas; this suggests that formation and availability of nursery habitat (e.g., backwaters) in the San Juan River is influenced by channel gradient.

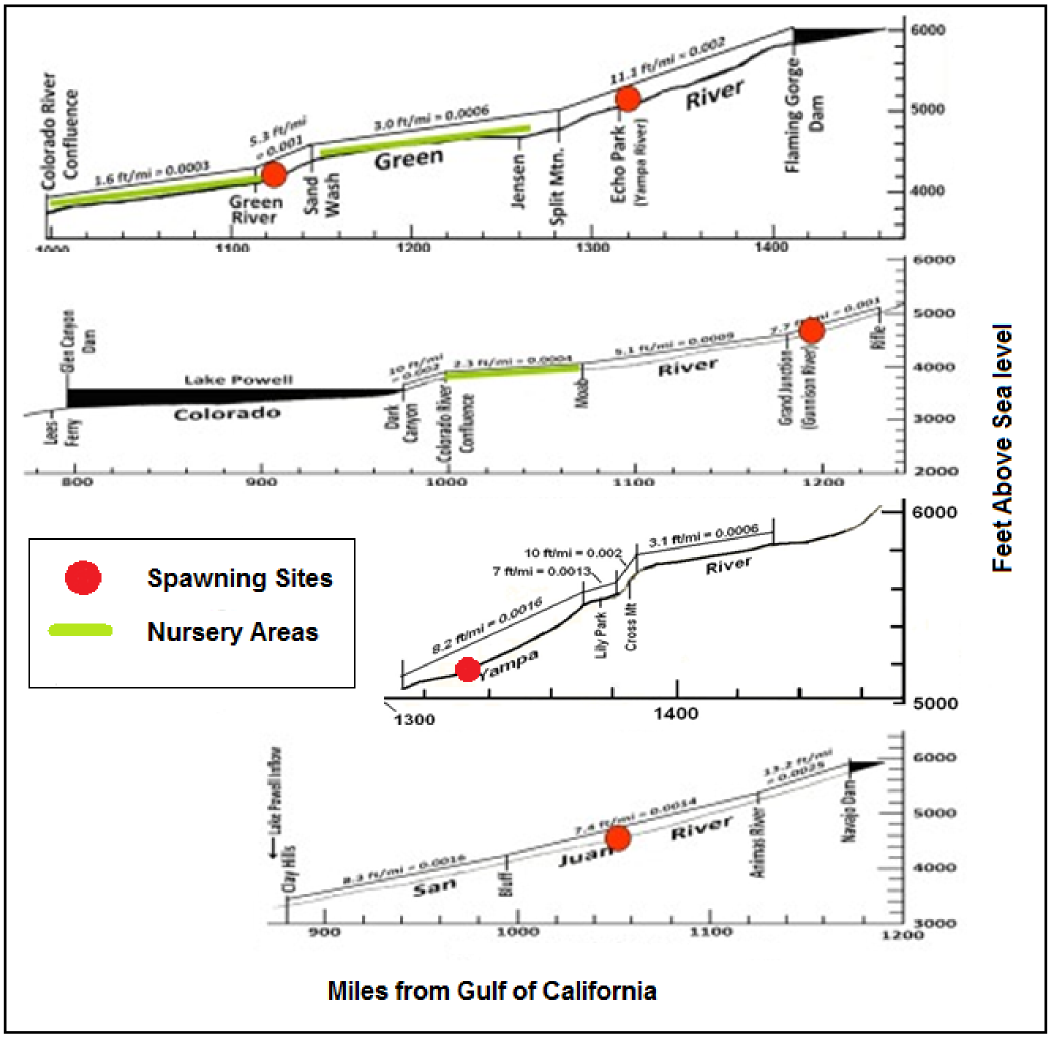

Figure 30. Gradients for spawning sites and nursery areas used by Colorado Pikeminnow in the Green River, Upper Colorado River, Yampa River, and San Juan River. Spawning sites and nursery areas from LaGory et al. (2003) and river gradients from U.S. Department of the Interior (1946).

13.2 Fish Passage

Colorado Pikeminnow in the Green and Upper Colorado rivers use different reaches for different life stages (Bestgen et al. 2010); e.g., in the Green River, spawning occurs in the canyons of the Yampa River, whereas nursery and rearing occurs in the alluvial sandy reaches of the middle and lower Green River. All reaches in the Green River are accessible to fish; the only diversion dam in occupied habitat at Tusher Wash was redesigned with fish passage in 2016. Fish passage has also been provided to all historic range in the Upper Colorado River with passage facilities at the Redlands Water and Power Company on the Gunnison River (selective fish passage completed in 1996); and the Grand Valley Irrigation Company (nonselective, 1998), Grand Valley Project (selective, 2004), and Price-Stubb (nonselective, 2008) on the Upper Colorado River.

Access to all reaches of the San Juan River up to Navajo Dam is impeded by 8 diversions or small dams (Figure 31; personal communication, Sharon Whitmore, USFWS). Colorado Pikeminnow occur over about 347 km of the San Juan River system, including the mainstem, from Farmington, New Mexico, downstream to Lake Powell, and the tributary Animas River, McElmo Creek, and Yellow Jacket Creek. Three physical barriers to fish movement on the mainstem have been modified to allow access to an additional 58 km of critical habitat, i.e., Cuedi Diversion (removed, 2001), Hogback Diversion (nonselective fish passage, 2001), and Public Service Company of New Mexico Weir (selective fish passage, 2003). Fish passage at two other mainstem barriers (i.e., Arizona Public Service Company Weir and Fruitland Diversion) are in the design phase that will allow access to an additional 288 km of critical habitat. Diversions on the Animas River also impede upstream movement into that river, including the Farmington Lake Diversion (RM 12) and the Farmer's Ditch Diversion (RM 22).

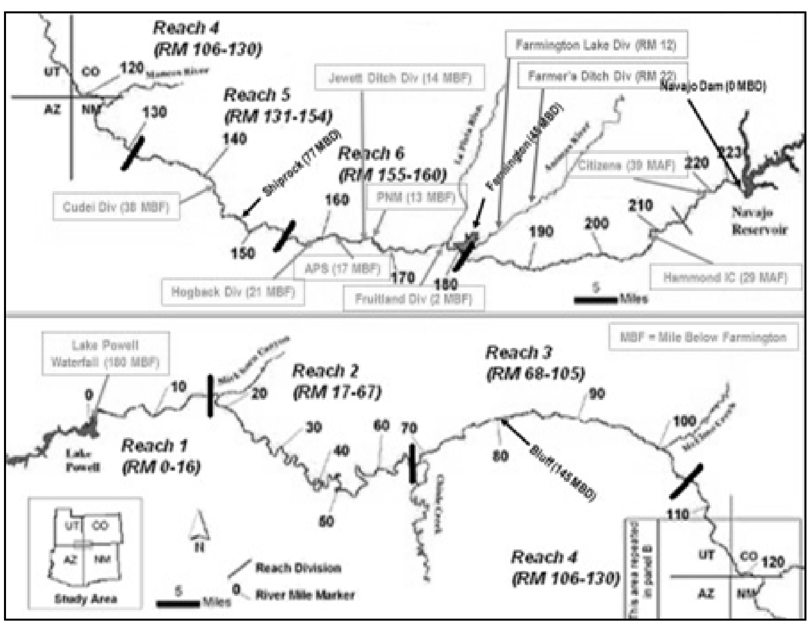

Figure 31. Locations of diversions that impede fish passage on the San Juan River.

Another impediment to movement is a waterfall that has formed in the San Juan arm of Lake Powell as a result of lowered reservoir elevation; sediment deposited at high reservoir elevation filled the historic river channel and the river has carved a new channel over hard rock formations and formed a steep drop in the river bed. This waterfall is an impediment to fish movement except when it is inundated by high lake levels.

13.3 Temperature Suitability

Modifications to the penstocks at Flaming Gorge Dam in 1976 provided the flexibility to release a mixture of warmer water and native fish, including Colorado Pikeminnow, have expanded upstream range in the upper Green River.

Cold releases from the Aspinall Unit dams on the Gunnison River may restrict use and upstream range by Colorado Pikeminnow in the Gunnison River (Osmundson 2011). Recent studies show that it is possible to meet downstream temperature targets in the Gunnison River through incorporation of a multiple-level selective withdrawal structure at Blue Mesa Dam (Hydrosphere Resource Consultants 2002; Boyer and Cutler 2004) that could allow for an expansion of the Colorado Pikeminnow population about 40 km upstream.

The temperature of the San Juan River cooled considerably after completion of Navajo Dam in 1962. Pre-dam temperature (1954) at Blanco (about 18 mi below Navajo Dam) was 20-25°C in summer and 0°C in winter; whereas post-dam temperature (1994) is 4-8°C in summer and 4°C in winter (Figure 32). The timing of warmest temperature in the San Juan River at Blanco has also shifted from pre-dam highs during Jun 1 – Sep 1 to post-dam highs during Aug 1 – Oct 1. A shift to warmest temperatures in late summer and fall reflects the warmest dam-release temperatures that result when fall overturn mixes warm surface water into the area of penstock withdrawals.

Expanding the range of the Colorado Pikeminnow upstream of Farmington will require warming releases from Navajo Dam. One option for warming temperature of the San Juan River is to modify releases from Navajo Dam with a temperature control device (Cutler 2006).

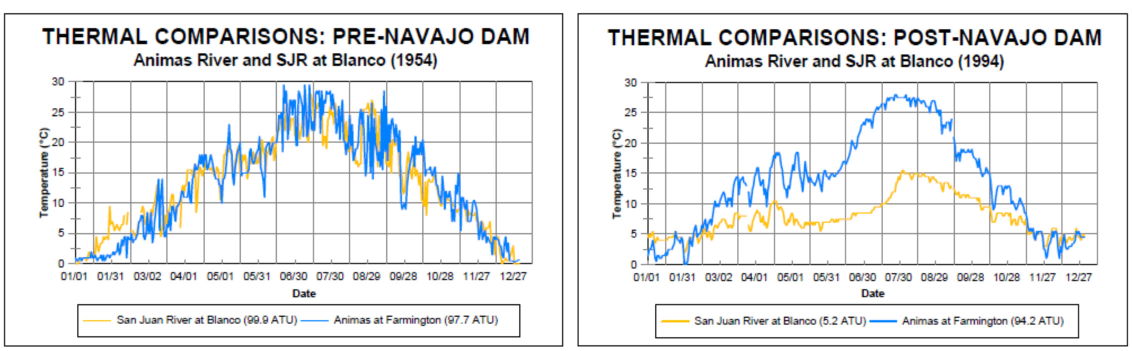

Figure 32. Temperature of the San Juan River before and after construction of Navajo Dam in 1962. Figures from Cutler (2006).

13.4 Mesohabitat Use

Colorado Pikeminnow live in warm reaches of the Colorado River mainstem and larger tributaries, and require uninterrupted passage for spawning migrations and dispersal of young. The species is adapted to a hydrologic cycle characterized by large spring peaks of snowmelt runoff and low, relatively stable base flows in summer and winter. Throughout most of the year, juveniles, subadults, and adults utilize relatively deep, low-velocity eddies, pools, and runs that occur in nearshore areas of main river channels (Tyus and McAda 1984; Valdez and Masslich 1989; Tyus 1990, 1991; Osmundson et al. 1995; Table 16). In spring, adults utilize floodplains, flooded tributary mouths, flooded side canyons, and eddies that are available only during high flows (Tyus 1990, 1991; Osmundson et al. 1995).

Table 16. Seasonal frequency (%) of use of mesohabitats in the Grand Valley of the Upper Colorado River subbasin by radio-tagged adult Colorado Pikeminnow, 1986–1989 (Osmundson et al. 1995). Habitats: FR = fast runs, SR = slow runs, RA = rapids, RI = riffles, ED = eddies, PO = pools, SH = shorelines, BA = backwaters, and GP = off-channel flooded gravel pits.

Months	Habitats (% of time used by radio-tagged fish)								
	FR	SR	RA	RI	ED	PO	SH	BA	GP
Apr–Jun (Spring)	3–19	13–32	0–1	0–2	2–9	8–12	3–8	22–42	3–25
Jul–Sep (Summer)	7–26	26–55	3–5	3–10	9–16	13–16	0–4	3–7	0–4
Oct (Fall)	0	61	0	0	4	26	0	9	0
Nov-Feb (winter)	0	27–41	0	0	0–8	42–62	0	5–15	0
March	4	43	0	0	7	32	0	14	0

13.5 Spawning Sites

Colorado Pikeminnow spawning sites in the Green River subbasin have been well documented. The two principal locations are in Yampa Canyon on the lower Yampa River and in Gray Canyon on the lower Green River (Tyus 1990, 1991). These reaches are 42 and 72 km long, respectively, but most spawning is believed to occur at one or two short segments within each of the two reaches. Another spawning area may occur in Desolation Canyon on the lower Green River (Irving and Modde 2000), but the location and importance of this area has not been verified.

Although direct observation of Colorado Pikeminnow spawning is not possible because of high turbidity, radiotelemetry indicates that spawning occurs over cobble-bottomed riffles (Tyus 1990). High spring flows and subsequent post-peak summer flows are important for construction and maintenance of spawning substrates (Harvey et al. 1993). In contrast with the Green River subbasin, where known spawning sites are in canyon-bound reaches, currently suspected spawning sites in the Upper Colorado River subbasin are at six locations in meandering, alluvial reaches (McAda 2003).

Two potential spawning areas were located in “the mixer area” at RM 131 and 132 during a radiotelemetry study of Colorado Pikeminnow on the San Juan River (Miller 1994). Three of four radio-tagged fish were simultaneously located at an island/chute/ eddy complex at RM 132 in mid-July 1993 and subsequently at a second site immediately downstream. Visual observations of a paired male and female were made that confirmed the radiotelemetry information. More recently, spawning-related activity has been seen in the San Juan River near the Four Corners area (~RM 120; personal communication, Scott Durst, USFWS).

After hatching and emerging from the spawning substrate, Colorado Pikeminnow larvae drift downstream to backwaters in sandy, alluvial regions, where they remain through most of their first year of life (Holden 1977; Tyus and Haines 1991; Muth and Snyder 1995). These backwaters are formed after spring runoff within the active channel and are not floodplain features. Colorado Pikeminnow larvae occupy these in-channel backwaters soon after hatching. They are most abundant in backwaters that are large, warm, deep (average, about 0.3 m in the Green River), and turbid (Tyus and Haines 1991). Such backwaters are created when a secondary channel is cut off at the upper end, but remains connected to the river at the downstream end. These chute channels are deep and may persist even when discharge levels change dramatically. An optimal river-reach environment for growth and survival of early life stages of Colorado Pikeminnow has warm, relatively stable backwaters, warm river channels, and abundant food (Muth et al. 2000).

13.6 Habitat Suitability Indices

Habitat suitability index curves were developed from two workshops of species experts using a Delphi Decision Process (Valdez et al. 1987). The specific metrics of each curve are provided in a hard copy report, but these data are not available electronically. The report provides a compilation of curves developed in the rivers of the upper basin, including the Green River (Holden 1977), San Juan River (Twedt and Holden 1980), Yampa and White rivers (Prewitt and Carlson 1980), Upper Colorado River (Valdez et al. 1982), and Yampa River (Rose 1984). Suitability indices for habitats used by Colorado Pikeminnow < 25 mm TL and 25−149 mm TL in the Upper Colorado River Basin (Figure 33; Valdez et al. 1987) illustrate the high degree of backwater use by age-0 fish. Habitat suitability curves for Colorado Pikeminnow in the San Juan River were developed by Miller (1995) using much of the information provided by Twedt and Holden (1980) and Valdez et al. (1987).

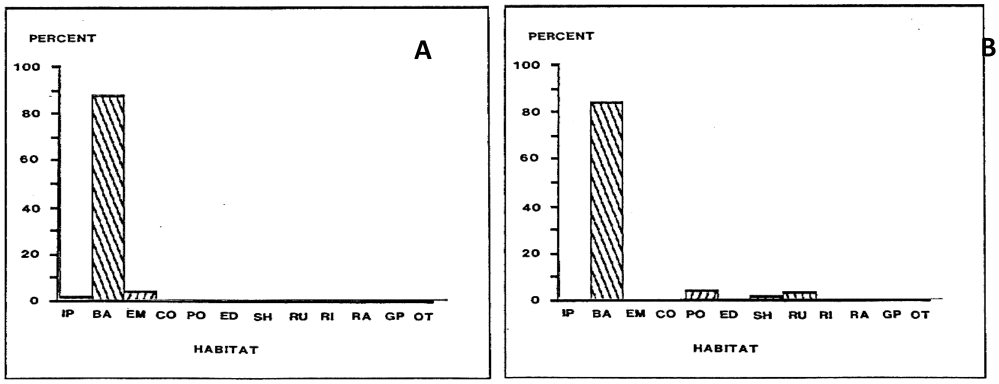

Figure 33. Suitability indices for habitats used by Colorado Pikeminnow (A) < 25 mm TL and (B) 25−149 mm TL in the Upper Colorado River Basin (Valdez et al. 1987).

13.7 Estimated Capacity of Backwater Habitat for Age-0 Fish

As shown in Figure 33, backwaters are the most common habitat used by Colorado Pikeminnow in their first year of life (i.e., age-0) in the Upper Colorado River Basin. Ecosystems Research Institute (ERI 2014) determined that the number and surface area of backwater habitats vary by year and geomorphic reach for the San Juan River during fall baseflow (Figure 34). For the period of measurements, the largest amount of backwater habitats measured during baseflow occurred in the fall 1995 and winter 1996. From the fall of 1996 to the fall of 2003, backwater surface area decreased substantially from a river wide high of 145,969 m^2 to a low of 20,294 m^2 in 2003 (i.e., 86% decrease). Since 2003, backwater habitat area has increased annually, reaching a post-2003 high of 67,786 m^2 in 2011 (ERI 2014). The average surface area of each backwater in the lower reach was only 32 m^2, accounting for 5,880 m^2 of backwater surface area (only 11% of the river-wide total compared to 29% in 2011).

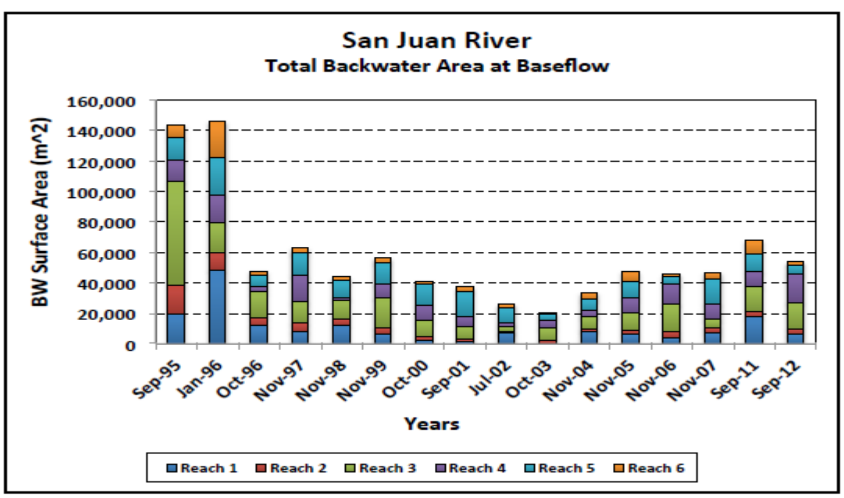

Figure 34. Densities of backwater habitats by year and geomorphic reach for the San Juan River, as measured during fall baseflow. Figure from Lamarra (2014).

Understanding the availability of backwater habitat in the San Juan River is important for knowing if nursery habitat may be limiting the Colorado Pikeminnow population. In order to estimate the numbers of age-0 Colorado Pikeminnow that could be supported in the San Juan River, a relationship was derived for the total numbers of age-0 Colorado Pikeminnow estimated from catch rates in backwaters < 400 m^2 of the Green and Upper Colorado rivers (Figure 35).

Only backwaters with surface area < 400 m^2 were included in the relationship to apply it to backwaters of comparable size in the San Juan River. Ecosystems Research Institute (ERI 2014) determined that most backwaters of the San Juan River are < 400 m^2 in size. The relationship derived from these data was used to estimate the numbers of age-0 fish that could be supported by backwaters in the San Juan River.

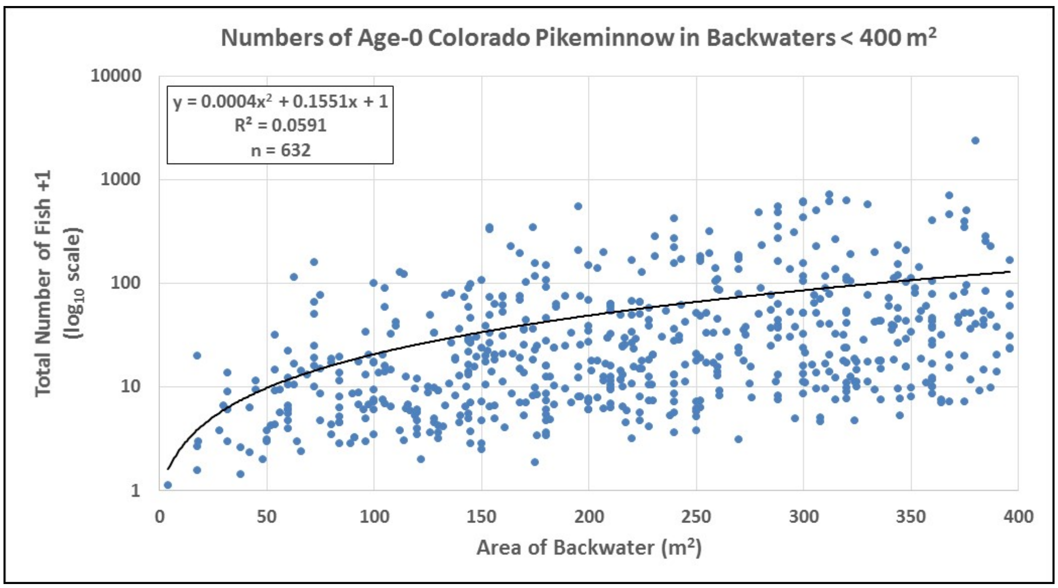

Figure 35. Numbers of age-0 Colorado Pikeminnow in 632 backwaters < 400 m^2 surface area of the Green and Upper Colorado rivers, 1986–2010. Data provided courtesy of Upper Colorado River Endangered Fish Recovery Program (Travis Francis, Database Manager, USFWS).

Data collected by ERI (2014) indicate that a high surface area and density (via counts) for backwaters were found in the lower 16 mi of the San Juan River although lower in 2012 than in 2011. The average surface area of each backwater in the lower reach was only 32 m^2, accounting for 5,880 m^2 of backwater surface area (only 11% of the river-wide total compared to 29% in 2011). In the non-canyon reaches of the San Juan River (3-6), large backwater complexes were found in Reaches 3 and 4. In Reach 3, densities average 10 per mile, with an average surface areas of just less than 100 m^2. The largest sized backwaters were found at RM 119 (7 backwaters with a total area of 7,532 m^2). This single river mile accounted for 15% of the total backwaters in the river. In addition, RM

122 and RM 133 had over 1,200 m^2 of backwater surface area with average sizes near 600 m^2.

The information provided by ERI (2014) was used to estimate the average size of backwaters for each of the six reaches of the San Juan River. The possible numbers of age-0 Colorado Pikeminnow in backwaters was computed on the basis of this average size of backwaters by reach as shown in Table 17. For the years 1995 and 1996 there was sufficient backwater habitat at base flows in the San Juan River for about 28,000 age-0 Colorado Pikeminnow. In subsequent years, total possible numbers of age-0 ranged from 4,359 to 13,469. The estimated numbers of age-0 Colorado Pikeminnow in backwaters of the San Juan River were derived from highly variable data from Upper Basin backwaters and from estimated average sizes of backwaters. Caution is advised in relying on these as actual numbers of fish possible; however, the apparent low magnitude of age-0 numbers suggests that total area of backwater habitat may limit recruitment of Colorado Pikeminnow in the San Juan River. Additional analyses of these and other data will be necessary to better understand availability of habitat for young Colorado Pikeminnow in the San Juan River.

Table 172. Total backwater area (a:), numbers of backwaters of average size (b:), and estimated numbers of age-0 Colorado Pikeminnow (c:) for each of six reaches of the San Juan River. River Miles by Reach: 1 = 2−16, 2 = 17−67, 3 = 68−105, 4 = 106−130, 5 = 131−154, 6 = 155−180. Total backwater area from ERI (2014).

Reach[a]	Sep-95	Jan-96	Oct-96	Nov-97	Nov-98	Nov-99	Oct-00	Sep-01	Jul-02	Oct-03	Nov-04	Nov-05	Nov-06	Nov-07	Sep-11	Sep-12
1 (32 m^2) a:	19,769	48,269	11,862	8,224	12,173	6,670	1,886	1,235	7,057	0	7,926	6,261	4,063	7,521	17,549	6,110
b:	617.78	1,508.41	370.69	257.00	380.41	208.44	58.94	38.59	220.53	0.00	247.69	195.66	126.97	235.03	548.41	190.94
c:	**3,319**	**8,104**	**1,992**	**1,381**	**2,044**	**1,120**	**317**	**207**	**1,185**	**0**	**1,331**	**1,051**	**682**	**1,263**	**2,946**	**1,026**
2 (30 m^2) a:	18,249	11,152	5,547	5,399	4,151	3,703	2,784	1,631	815	2,060	1,631	2,791	3,943	3,025	3,617	3,728
b:	608.30	371.73	184.90	179.97	138.37	123.43	92.80	54.37	27.17	68.67	54.37	93.03	131.43	100.83	120.57	124.27
c:	**3,049**	**1,863**	**927**	**902**	**694**	**619**	**465**	**273**	**136**	**344**	**273**	**466**	**659**	**505**	**604**	**623**
3 (100 m^2) a:	68,406	20,300	16,473	13,860	12,433	19,761	10,339	8,608	3,667	8,359	7,952	10,937	17,913	5,453	16,415	17,397
b:	684.06	203.00	164.73	138.60	124.33	197.61	103.39	86.08	36.67	83.59	79.52	109.37	179.13	54.53	164.15	173.97
c:	**13,346**	**3,961**	**3,214**	**2,704**	**2,426**	**3,855**	**2,017**	**1,679**	**715**	**1,631**	**1,551**	**2,134**	**3,495**	**1,064**	**3,203**	**3,394**
4 (300 m^2) a:	14,029	17,797	3,540	17,452	1,784	8,797	10,543	6,694	1,809	5,296	4,293	9,822	13,306	9,847	9,805	18,728
b:	46.76	59.32	11.80	58.17	5.95	29.32	35.14	22.31	6.03	17.65	14.31	32.74	44.35	32.82	32.68	62.43
c:	**3,859**	**4,896**	**974**	**4,801**	**491**	**2,420**	**2,900**	**1,842**	**498**	**1,457**	**1,181**	**2,702**	**3,660**	**2,709**	**2,697**	**5,152**
5 (150 m^2) a:	14,971	24,723	7,519	14,473	10,796	14,375	13,951	16,152	10,453	3,378	7,336	10,990	5,047	16,958	11,662	5,897
b:	99.81	164.82	50.13	96.49	71.97	95.83	93.01	107.68	69.69	22.52	48.91	73.27	33.65	113.05	77.75	39.31
c:	**3,220**	**5,318**	**1,617**	**3,113**	**2,322**	**3,092**	**3,001**	**3,474**	**2,248**	**727**	**1,578**	**2,364**	**1,086**	**3,648**	**2,508**	**1,268**
6 (30 m^2) a:	8,299	23,727	2,838	3,400	2,439	3,075	1,333	3,153	2,191	1,201	4,362	6,494	1,540	4,148	8,738	1,774
b:	276.63	790.90	94.60	113.33	81.30	102.50	44.43	105.10	73.03	40.03	145.40	216.47	51.33	138.27	291.27	59.13

c:	**1,387**	**3,965**	**474**	**568**	**408**	**514**	**223**	**527**	**366**	**201**	**729**	**1,085**	**257**	**693**	**1,460**	**296**
Total Area:	143,723	145,968	47,779	62,808	43,776	56,381	40,836	37,473	25,992	20,294	33,500	47,295	45,812	46,952	67,786	53,634
Total Age-0:	**28,181**	**28,107**	**9,198**	**13,469**	**8,384**	**11,620**	**8,923**	**8,002**	**5,149**	**4,359**	**6,643**	**9,803**	**9,839**	**9,882**	**13,419**	**11,760**
Mean Q	1,193	783.4	1,273	1,175	1,494	910.1	1,273	646.3	410.7	633.4	796.3	908	979	1,086	896.5	767.4

[a] average backwater area (m^2) for each reach was determined from information provided by ERI (2014)

The linkage between numbers of age-0 Colorado Pikeminnow in backwaters and baseflows of the San Juan River is a positive relationship with close association for all years sampled, except for Sep-95 and Jan-96, years that were preceded by high flows that scoured the channel and increased backwater numbers and area (ERI 2014; Figure 36). At baseflows seen from 1996 to 2012, the maximum number of age-0 Colorado Pikeminnow that can be supported in backwaters of the San Juan River is < 15,000.

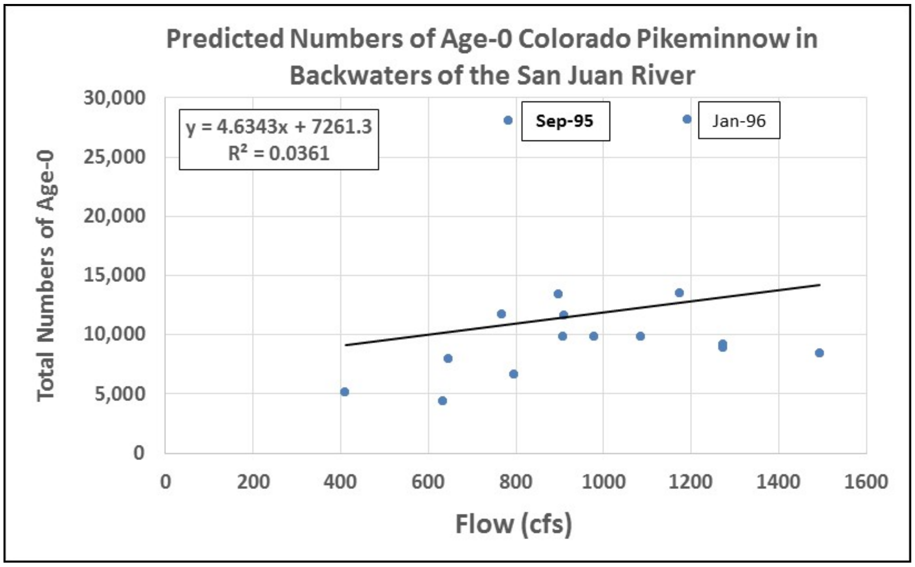

Figure 36. Predicted numbers of age-0 Colorado Pikeminnow in backwaters of the San Juan River at base flows.

An assessment of the abundance of age-0 native fish species and nursery habitat quality and availability in the San Juan River was conducted by Archer et al. (2000). The information contained in that report provides a good background assessment of the availability of nursery habitat that is supplemented by ERI (2014) and is important to consider in future analysis of nursery habitat in the San Juan River. Table 13 from Archer et al. (2000) is provided to illustrate the similar habitat areas compared to ERI (2014) as shown in Table 18.

Table 18. Total area (m2) of low-velocity habitats in nursery habitat study sections in the San Juan River, April 1994-1997. Table from Archer et al. (2000).

Reach	1994	1995	1996	1997
1	7,418	5,629	4,878	6,263
2	2,794	911	2,675	5,227
3	1,350	3,917	4,580	6,198
4	NA	NA	3,800	16,170

14.0 Genetics

14.1 Genetic Diversity

The only detailed genetics investigations of the Colorado Pikeminnow examined the relationships between hatchery fish and wild populations shortly after the species was first taken into captivity (Ammerman and Morizot 1989); and among two captive groups and samples of wild individuals after some stocking of hatchery fish (Williamson et al. 1999; Morizot et al. 2002). Ammerman and Morizot (1989) used starch gel electrophoresis and found that samples of fish from the Green and Upper Colorado rivers were similar genetically to two hatchery stocks first established in 1973 and 1978 (unbiased genetic identity = 0.99; Nei 1978), indicating that the fish initially used to develop a hatchery broodstock were genetically representative of the wild population. At least 9 of the 44 presumptive loci were polymorphic, and average heterozygosities were high (2.6-5.3%) for an endangered species.

Morizot et al. (2002) evaluated the genetic relationships among two captive populations of Colorado Pikeminnow from the Dexter National Fish Hatchery and Technology Center, New Mexico, and 15 samples of wild adult, juvenile, and age-0 fish from the Green, Yampa, Colorado, and San Juan rivers. The products of 89 or more loci were resolved by starch gel electrophoresis and histochemical staining; 8 loci were polymorphic in at least one sample. This comparison of genetic diversity through allozyme techniques showed little difference among the populations of the Upper Colorado River Basin (Williamson et al. 1999; Morizot et al. 2002), but the authors stressed the need to maintain local adaptability of several populations in any potential broodstock program.

Allele frequencies from 633 wild fish and 94 hatchery fish did not differ significantly among geographically separated breeding populations, suggesting essential panmixia of the Colorado Pikeminnow across the four rivers sampled (i.e., Green, Yampa, Colorado, and San Juan; Morizot et al. 2002). FST values are a measure of genetic differentiation among populations with values ranging from 0 (no difference) to 1 (complete differentiation), and are directly related to variance in allele frequency. Mean FST values ranged from 0.003 among wild age-0 Green River and Colorado River fish (n = 426) to 0.108 among all wild adults (n = 207) and captive broodstock (n = 60).

Significant deviations from Hardy−Weinberg equilibrium were observed at four loci in the Colorado River and Green River samples of adults, juveniles, and age-0 fish, although no hatchery samples showed such deviations. The most striking geographic variability observed was the presence of the rare private alleles GR*b and TPI-2*c in Green River samples and GPI-2*c, PEPB*a, and PEPS*b in Colorado River samples. The lowest genetic variability was observed in the San Juan River samples, possibly the result of prior population bottlenecks.

14.2 Genetic Effective Population Size (N_e)

An N_e of 500 is commonly used for fishes (Waples 1990; Bartley et al. 1992; Allendorf et al. 1997) and other vertebrate species (Mace and Lande 1991; Ralls et al. 1996), and has been used as the basis for deriving an estimate of N_e for other endangered fishes (e.g., Reiman and Allendorf 2001). Using an N_e of 500, a 1.11:1 sex ratio, and an N_e/N_g ratio of 0.20, an adjusted N_e of 2,510 adults (i.e., 502/0.20, rounded to 2,500) was derived as the estimated number of adult Colorado Pikeminnow necessary to maintain a genetic effective population size.

To maintain an N_e of 500 with a 1.11:1 sex ratio, the total number of breeding adults (N_b) must be increased according to the following relationship:

$N_e = 4M_bF_b/M_b+F_b$

Where: M_b = number of breeding males,

F_b = number of breeding females, and

$N_b = M_b + F_b$.

Hence: $N_e = 4\,(264)(238)/502 = 500$ (i.e., 264 males and 238 females are needed to maintain an N_e of 500).

In a letter to the USFWS dated 21 May 1998, Dr. Robert C. Lacy, Department of Conservation Biology, Chicago Zoological Society, recommended an N_e/N_g of 0.20 for Colorado Pikeminnow based on the average for salmonids reported by Allendorf et al. (1997).

An adjusted N_e was computed for the Colorado Pikeminnow using the genetic parameters described above (USFWS 2014):

Adjusted $N_e = N_e/(N_e/N_g)$

Where: N_e = genetic effective population size, 502;

N_e/N_g = proportion of adults contributing genes to

next generation (~0.20 from R. Lacey, 1998);

15.0 Parasites and Diseases

A survey of diseases and parasites of endangered fishes in the Upper Colorado River Basin in 1981 (Flagg 1982) revealed that Colorado Pikeminnow are infected by a variety of parasites, but none appear to singly lead to death of individuals. The principal parasites are an intestinal tapeworm and an external parasitic copepod, and the protozoans *Myobolus* sp. and *Trichodina sp.*, as well as the trematode *Ornithodiplostomum* sp. Bass tapeworms (*Proteocephalus ambloplites*) were found in 65% of stomachs from fish larger than 200 mm TL in the Green River (Vanicek 1967). Vanicek (1967) also reported that P. Dotson (unpublished data, Utah Department of Fish and Game, Salt Lake City, 1962) found tapeworms in 80% of Colorado Pikeminnow examined. A cestode identified as *Proteocephalus ptychocheilus* was found in Colorado Pikeminnow from the upper basin (Flagg 1982). This may be the same species reported by Vanicek (1967), but further study has not been conducted to resolve the taxonomic discrepancy. Osmundson (1987) reported the first occurrence of Asian tapeworm (*Bothriocephalus achielognathii*) in hatchery-raised Colorado Pikeminnow stocked in riverside ponds along the Upper Colorado River. Asian tapeworms were identified in wild Colorado Pikeminnow from the Colorado River downstream of Moab, Utah, in 1991 (personal communication, D. Osmundson, USFWS). The parasitic copepod (*Lernaea cyprinacea*) is common in Colorado Pikeminnow and has been reported by several investigators (Hagan and Banks 1963; Vanicek 1967; Flagg 1982). This parasite is believed to be alien to the Colorado River Basin, and transferred from other river basins via non-native fishes.

16.0 Diet

Adult Colorado Pikeminnow are considered piscivores and the main historic predator of the Colorado River Basin (Vanicek and Kramer 1969; Minckley 1973; Holden and Wick 1982). Adults reach a large size with a large mouth capable of ingesting the largest fish native to the system; however, as a member of the minnow family, Colorado Pikeminnow lack jaw, vomerine, and palatine teeth, and instead possess large pharyngeal teeth located on the first modified gill arch at the base of the throat. The teeth of this "pharyngeal mill" overlap with the swallowing action of the fish and serve to masticate and force food into the gullet.

Young Colorado Pikeminnow consume mainly insects and crustaceans but quickly transition their diet to fish with size and age. The principal food items of young up to about 50 mm TL in nursery backwaters are cladocerans, copepods, and midge larvae (Vanicek 1967; Jacobi and Jacobi 1982; Muth and Snyder 1995). Insects became important for fish up to about 100 mm TL, after which fish are the main food item. Vanicek (1967) reported Colorado Pikeminnow as small as 50 mm TL with fish remains in their guts, and Muth and Snyder (1995) reported fish remains in the gut of a Colorado Pikeminnow 21 mm TL. Young in hatchery troughs may become cannibalistic at sizes of less than 50 mm TL (personal communication, F. Pfeifer, USFWS).

Adults consume primarily soft-rayed fishes, including bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (*C.latipinnis*), red shiner, sand shiner, and fathead minnow (Osmundson 1999). Colorado Pikeminnow have also been reported with channel catfish lodged in their throat that may be a cause of death for the Pikeminnow (McAda 1980; Pimental et al. 1985). Colorado Pikeminnow have been caught by anglers using various baits, including Mormon crickets (*Anabrus migratorius*; Tyus and Minckley 1988); carcasses of mice, birds, and rabbits (Beckman 1963); and artificial lures and spoons (Quartarone 1995).

17.0 Water Quality

17.1 Selenium

Selenium contamination is a water-quality factor that impacts localized portions of endangered fish populations in the Colorado River System (USFWS 1998, 2002b). Selenium is a naturally occurring element that is required at low concentrations by all life forms, but at high concentration in streams and lakes, it can lead to reduced reproduction and deformities in fish and in waterfowl. In the Upper Colorado River Basin, selenium comes from the Mancos shale where it is picked up by water seeping from canals and ponds, and percolating through soils beneath irrigated fields and lawns (B. Osmundson et al. 2000). It is shown to adversely affect reproduction and recruitment in freshwater fish species (e.g., Lemly 1996; Hamilton 2003; Holm et al. 2003, 2005; Palace et al. 2004a, 2004b; Hinck et al. 2007).

The effects of selenium on various life stages of the Colorado Pikeminnow have been investigated (Hamilton 1995; Hamilton et al. 2003, 2004). Hamilton (1999) hypothesized that historic selenium contamination of the upper and lower Colorado River basins contributed to the decline of these endangered fish by affecting their overall reproductive success. Levels of selenium contamination in certain reaches of endangered fish critical and occupied habitat exceed those shown to impact fish and wildlife elsewhere (e.g., Stephens et al. 1992; Stephens and Waddell 1998; Thomas et al. 1998; Simpson and Lusk 1999; U.S. Bureau of Reclamation 2006; Thomas et al. 2008). Tissue samples from endangered fish inhabiting the San Juan River (Simpson and Lusk 1999) and from grow-out ponds of the Upper Colorado River (B. Osmundson et al. 2008) had selenium concentrations greater than toxicity guidelines for fish muscle tissue suggested by Lemly (1996) and NIWQP (1998) for protection of reproductive health in freshwater fish. The EPA and individual states have water quality standards for selenium toxicity; current EPA chronic selenium standards of 5 µg/L total and 4.6 µg/L dissolved are under review.

In 1994, muscle plugs were collected from a total of 39 Colorado Pikeminnow captured at various Colorado River sites in the Grand Valley for selenium residue analysis (Osmundson et al. 2000). The muscle plugs collected from 16 Colorado Pikeminnow captured at Walter Walker State Wildlife Area (WWSWA) contained a mean selenium concentration of 17 µ/g dry weight, which was over twice the recommended toxic threshold guideline concentration of 8 µ/g dry weight in muscle tissue for freshwater fish. Because of elevated selenium concentrations in muscle plugs in 1994, a total of 52 muscle plugs were taken during 1995 from Colorado Pikeminnow staging at WWSWA. Eleven of these plugs were from fish previously sampled in 1994. Selenium concentrations in 9 of the 11 recaptured fish were significantly lower in 1995 than in 1994. Reduced selenium in fish may in part be attributed to higher instream flows in 1995 and lower water selenium concentrations in the Colorado River in the Grand Valley. In 1996, muscle plugs were taken from 35 Colorado Pikeminnow from WWSWA, and no difference in mean selenium concentrations were detected from those sampled in 1995.

Some tributaries to the San Juan River carry higher concentrations of selenium than found in the mainstem (Thomas et al. 1998). Increased selenium concentrations may also result from the introduction of groundwater to the mainstem of the river along its course (Keller-Bliesner, Inc. 1999). Although these levels are diluted by the flow of the San Juan River, the net impact is a gradual accumulation of the element in the river as it travels downstream. For example, concentrations of selenium in water samples collected from the mainstem San Juan River exhibited a general increase in maximum recorded values with distance downstream from Archuleta, New Mexico, to Bluff, Utah, (<1 microgram per liter [µg/L] to 4 µg/L) (Wilson et al. 1995). The safe level of selenium concentrations for protection of fish and wildlife in water is considered to be <2 µg/L, and chronically toxic levels are considered to be >2.7 µg/L (Lemly 1993; Maier and Knight 1994; Wilson et al. 1995). Diet is the primary source for selenium in fish (Lemly 1993; Hamilton and Buhl 1995). Thus, sediment and biotic analyses are necessary to further elucidate the risk of selenium in water to fish and wildlife.

17.2 Mercury

The impact of mercury (or the functional relationship of mercury and reproductive impairment) on the Colorado Pikeminnow was derived for purposes of the PVA and is described in the PVA report by Miller (2014). Figures 37-43 and Table 19 are excerpted from the PVA Report.

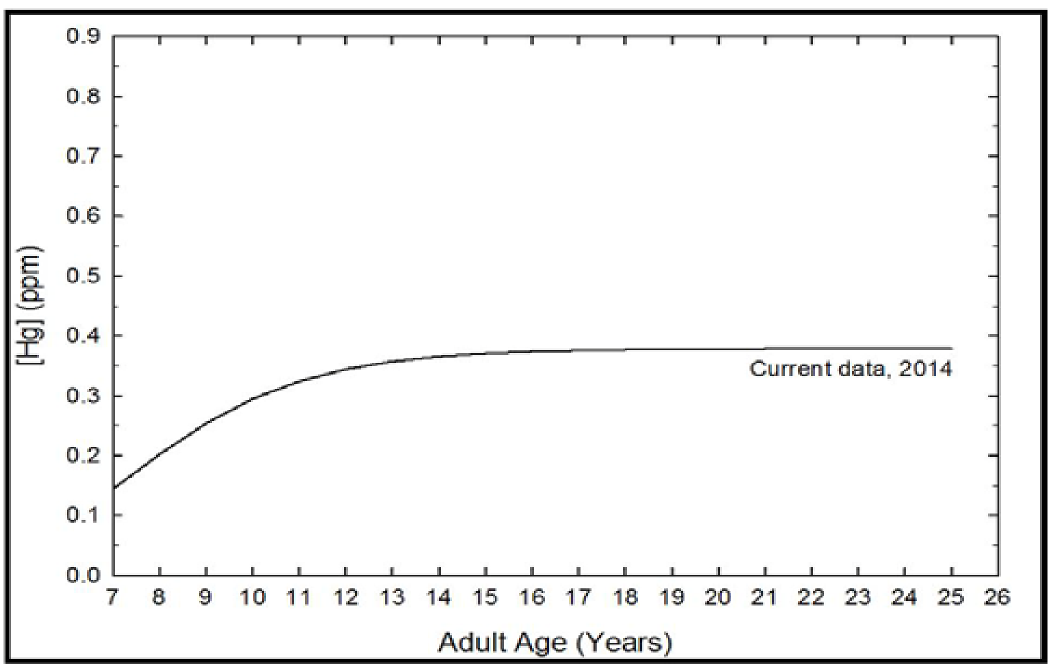

Figure 37. Whole-body mercury (Hg) burden among adult Colorado Pikeminnow as a function of age. See accompanying text and Appendix C for more information on deriving the proposed relationship. Figure A-1 from Miller (2014).

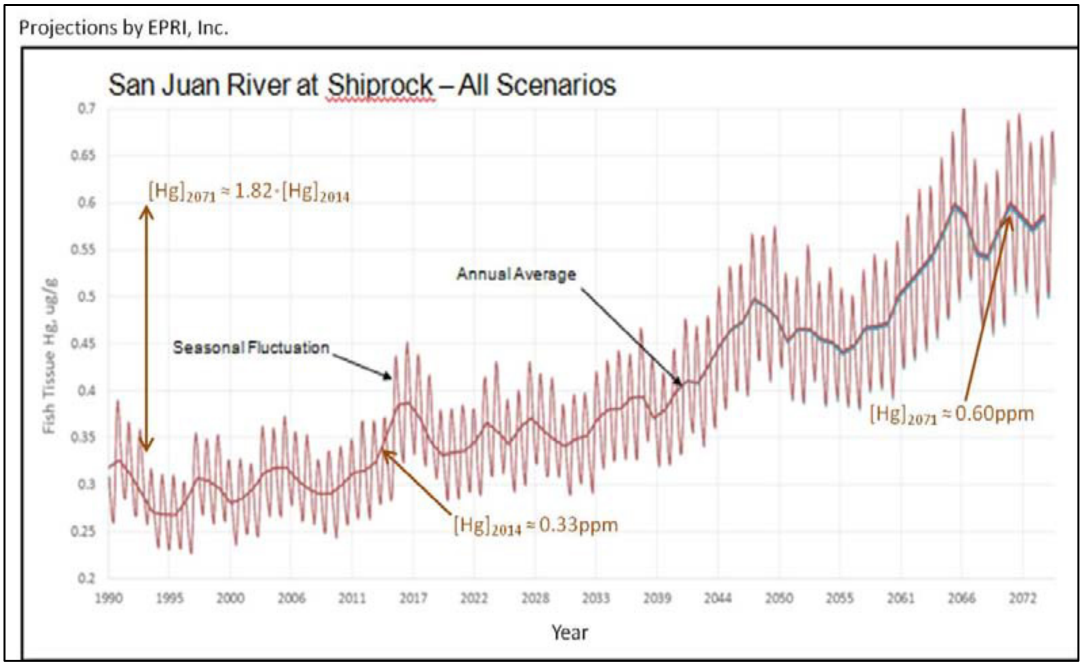

Figure 38. Projection of environmental Hg burden in adult Colorado Pikeminnow in the San Juan River. See accompanying text for additional information. Figure A-2 from Miller (2014).

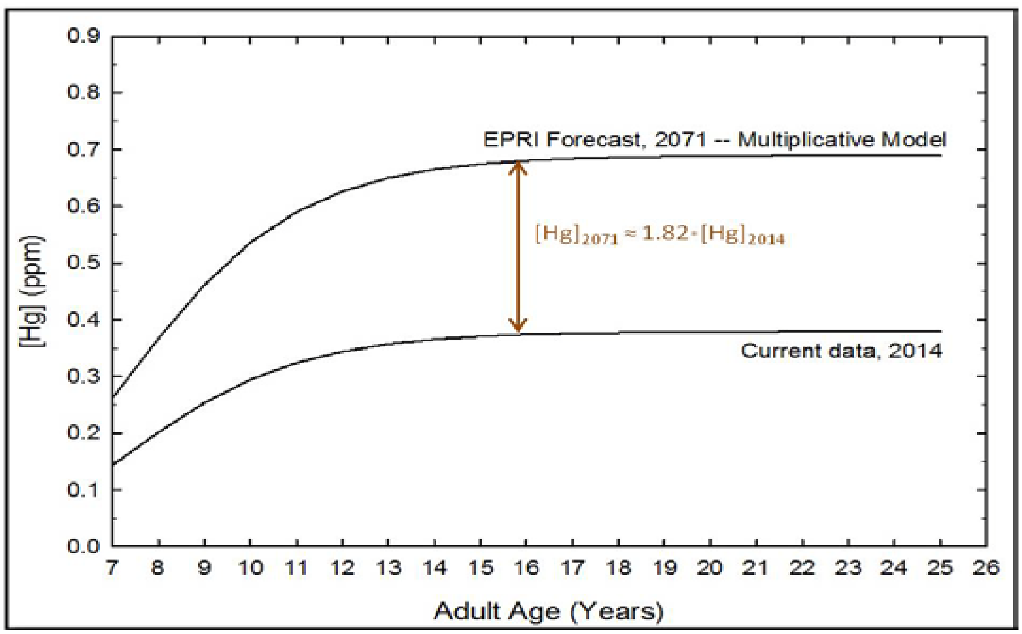

Figure 39. Whole-body mercury (Hg) burden among adult Colorado Pikeminnow as a function of age, assuming either constant environmental Hg burden through time (2014 dataset) or gradual increase in environmental Hg burden into the future (2071 dataset). See accompanying text and Appendix C for more information on deriving the proposed relationship. Figure A-3 from Miller (2014).

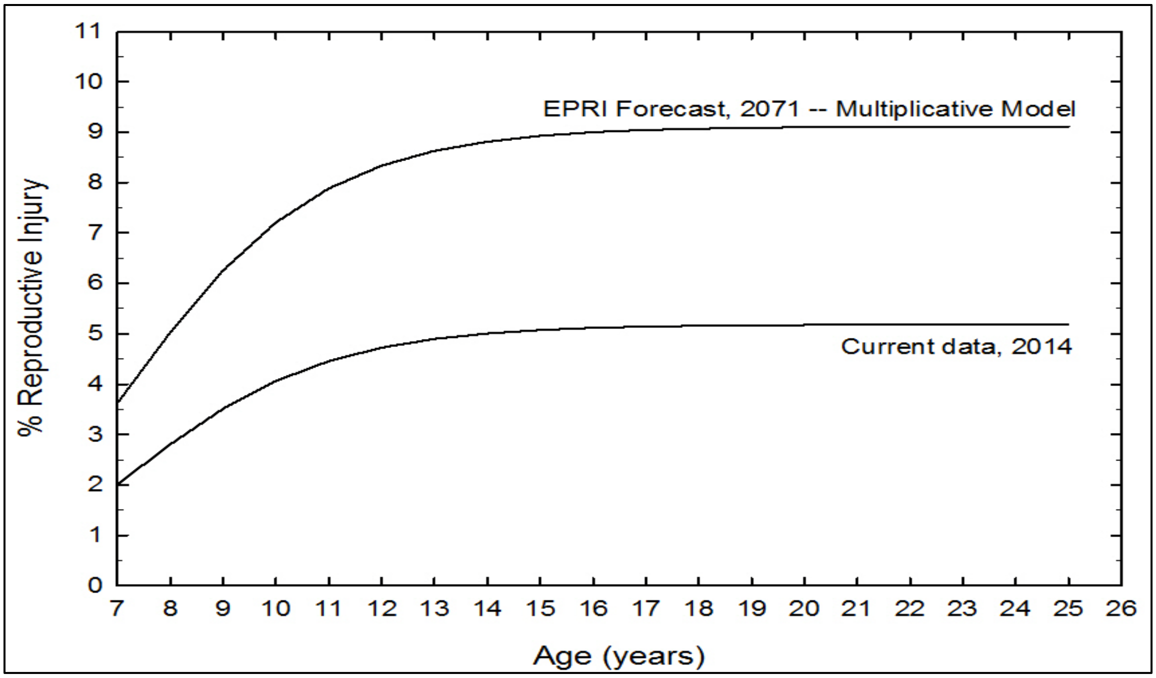

Figure 40. Percent reproductive injury as a function of adult age among Colorado Pikeminnow in the San Juan River, assuming either constant environmental Hg burden through time (2014 dataset) or gradual increase in environmental Hg burden into the future (2071 dataset). See accompanying text and Appendix C for more information on definitions of terms and methods for deriving the proposed relationship. Figure A-4 from Miller (2014).

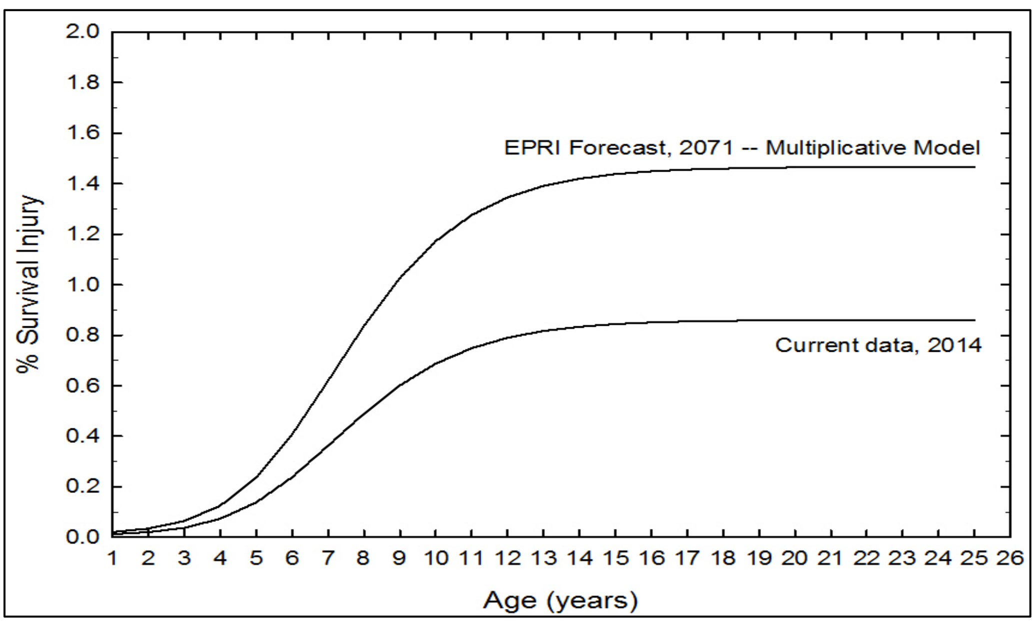

Figure 41. Percent survival injury as a function of age among Colorado Pikeminnow in the San Juan River, assuming either constant environmental Hg burden through time (2014 dataset) or gradual increase in environmental Hg burden into the future (2071 dataset). See accompanying text and Appendix C for more information on definitions of terms and methods for deriving the proposed relationship. Figure A-5 from Miller (2014).

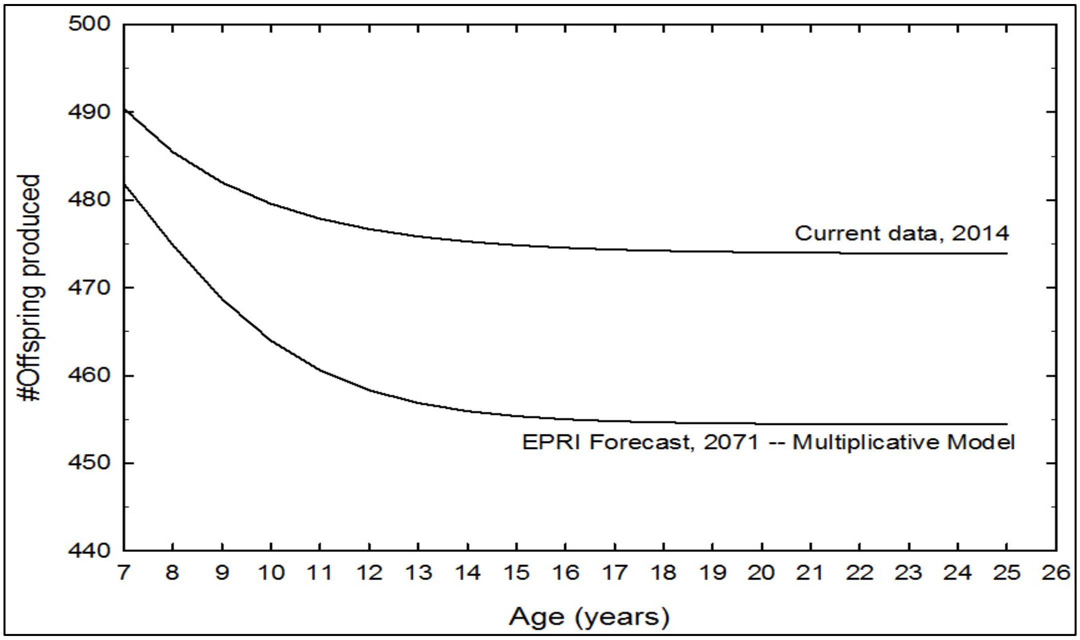

Figure 42. Offspring production per successfully spawning adult as a function of adult age among Colorado Pikeminnow in the San Juan River, assuming either constant environmental Hg burden through time (2014 dataset) or gradual increase in environmental Hg burden into the future (2071 dataset). See accompanying text and Appendix C for more information on deriving the proposed relationship. Figure A-6 from Miller (2014).

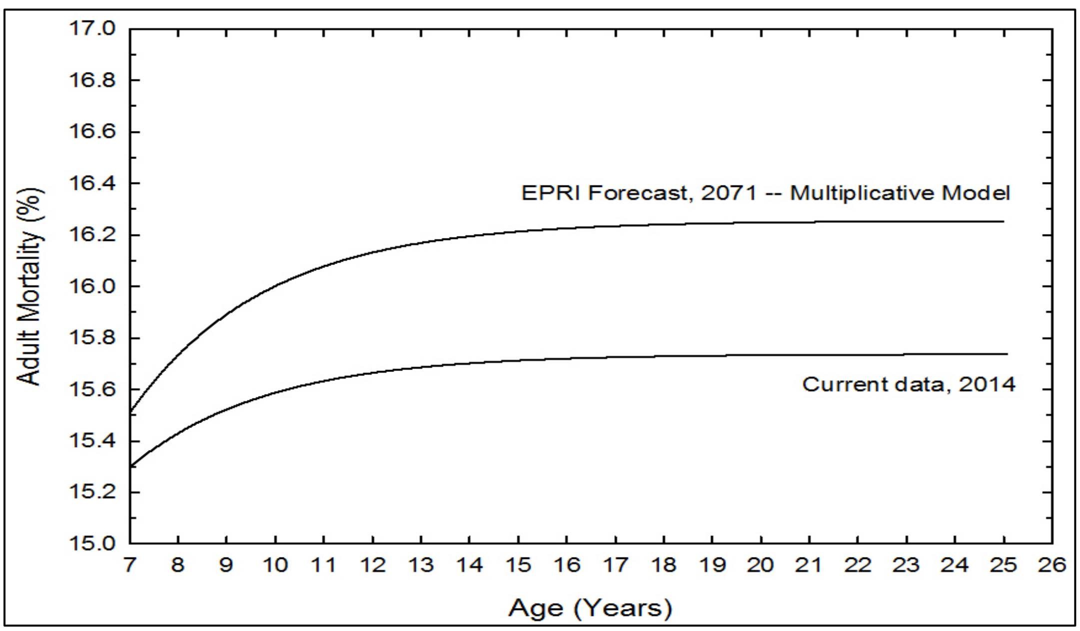

Figure 43. Adult mortality as a function of age among Colorado Pikeminnow in the San Juan River, assuming either constant environmental Hg burden through time (2014 dataset) or gradual increase in environmental Hg burden into the future (2071 dataset). See accompanying text and Appendix C for more information on deriving the proposed relationship. Figure A-7 from Miller (2014).

Table 19. Simulating Hg-mediated impairment of subadult survival in Colorado Pikeminnow. Columns labeled "2014" and "2071" give predicted mortality rates under conditions of Hg-mediated demographic impairment in simulation years 2014 and 2071 (timesteps 1 and 58), respectively. Right-hand column gives the formula specifying the linear increase in mortality across the range defined in the previous two columns. Note that these subadult survival modifications are made at the same time that much larger changes are made to adult survival. See accompanying text for additional information. Table A-1 from Miller (2014).

Age (*x*)	Unimpaired	2014	2071	Mortality Formula
1	89.0	89.001	89.002	= 89.001+(MIN(0.0000165*Y;0.001))
2	78.0	78.004	78.008	= 78.004+(MIN(0.000055*Y;0.004))
3	67.0	67.012	67.021	= 67.012+(MIN(0.000153*Y;0.009))
4	45.0	45.040	45.069	= 45.040+(MIN(0.000494*Y;0.029))
5	30.0	30.097	30.166	= 30.097+(MIN(0.00119*Y;0.069))
6	18.0	18.195	18.334	= 18.195+(MIN(0.00239*Y;0.139))

18.0 Mortality Rates

18.1 Green River Subbasin

Bestgen et al. (2005, 2010) estimated average annual survival for adult males and females (≥ 450 mm TL) from the Green River subbasin as 82% during 1991–1999, 65% during 2001–2003, and 80% during 2006–2008 (Table 20, Figure 44). From 2000 to 2003, the population declined from 4,084 to 2,142 adults for an apparent decline of 48%. Recruitment was low during that period, with the proportion of recruits (400–449 mm TL) < 10% of the adult population, far less than the estimated average annual adult mortality of 35%. Reasons for this decline are not understood, but the low recruitment was concurrent with drought conditions leading to low stream flows and increases in numbers and distributions of non-native fishes, such as smallmouth bass (*Micropterus dolomieu*), particularly in the Yampa River, the principal spawning area for this population. For the period 2003 to 2008, the population of Colorado Pikeminnow increased from 2,142 to 3,672 adults, an apparent increase of 71%, and overall the population increased slightly. Abundance of recruits during 2006–2008 averaged 22% (17.4% to 30.4%) of estimated adult abundance, which was more than sufficient to offset overall estimated adult mortality (20%).

Table 20. Survival of all Colorado Pikeminnow captured (>150 mm TL). From Bestgen et al. (2010).

Period	Survival	95% CI
1991-1999	0.82	0.71 to 0.89
2000-2003	0.65	0.59 to 0.71
2006-2008	0.80	0.60 to 0.91

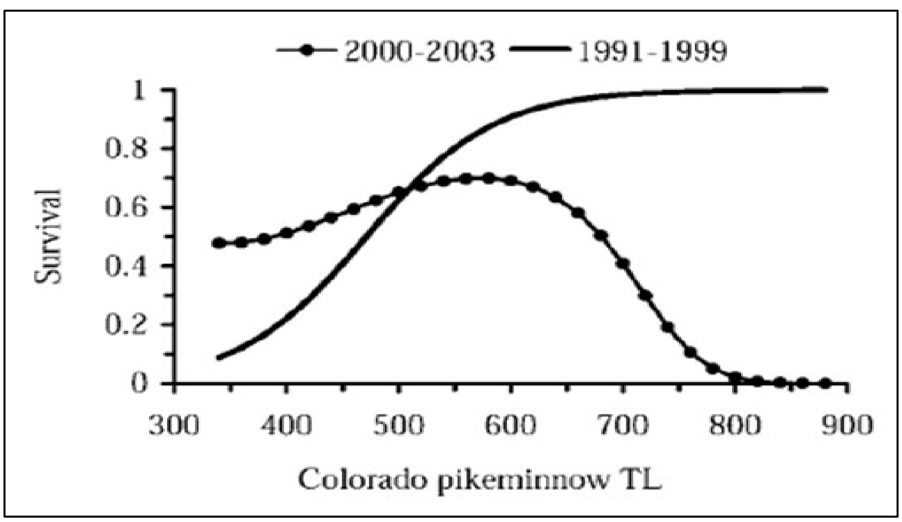

Figure 44. Survival rate of Colorado pikeminnow as a function of TL (mm) in the Green River basin in 1991–1999 and 2000–2003. The 1991–1999 data were collected during Interagency Standardized Monitoring Program (ISMP) sampling; data from other periods were collected during abundance estimation sampling. Fig. 4 from Bestgen et al. (2007).

There was a clear differences in survival rates for the periods 1991-1999 and 2000-2003 (Table 21). During 1991-1999, the Green River population was expanding due to high recruitment and good environmental conditions. This is in contrast to lower survival rates during 2000-2003 when the population declined and the environment went to drought.

It is believed that difference in survival for the two periods was due to drought and perhaps lower food abundance (see reduced length-weight relationships in section 6.0 Length and Weigh) and perhaps effects of predators on survival. Possibly, one might parse the difference into drought effects and non-native fish effects; e.g., 50:50? This is mainly for larger-bodied fish.

Table 21. Survival of Colorado Pikeminnow as shown in Figure 45 above. From Bestgen et al. (2007). Estimates of survival computed from a logistical regression available in a companion spreadsheet.

Length	survival 2000-2003	survival 1991-1999
340	0.48	0.09
400	0.51	0.22
500	0.65	0.63
600	0.69	0.91
700	0.41	0.98
800	0.02	0.997
900	2.34E-05	0.999

Overwinter survival of age-0 fish showed a significant relationship between densities in the fall and spring, suggesting that high spawning success and egg and larval survival by fall (i.e., 3–4 months of age) largely determine cohort strength (Valdez et al. 1999; Converse et al. 1999; McAda and Ryel 1999). Overwinter survival also influences cohort strength, but the linkage to environmental correlates (e.g., flow variability, river temperature and ice formation, average backwater depth, and non-native fish density) was unclear. Overwinter survival (October–March) of age-0 fish in backwaters of the upper Green River, based on the difference between fall and spring seine catch rates for 1989, 1990, 1991, 1992, and 1993 was 96, 29, 31, 38, and 62% (mean, 51%), respectively (Valdez et al. 1999). Survival was highest (85%) in backwaters deeper than 120 cm and lowest survival (18%) in backwaters less than 30 cm deep.

18.2 Upper Colorado River Subbasin

Osmundson and White (2009) estimated survival of adults ≥ 500 mm TL as 88.2% (95% CI = 85–91%) during 1991–1994, 85.9% (95% CI = 81–89%) during 1998–2000, and 80.4% (95% CI = 66–90%) during 2003–2005 (Figure 45). The Upper Colorado River population ranged from a low of 440 adults in 1992 to a high of 889 in 2005 (Osmundson and White 2009). During 2003–2005, the estimated number of adults was 661 in 2003, 688 in 2004, and 889 in 2005, with a 3-year average of 746. The average annual survival of adults over the three sample periods was 85%, and annual abundance of recruits (400–449 mm TL) exceeded annual adult mortality in 6 of the 9 years. When annual gains and losses were summed for 1992–2005, there was an estimated net gain of 332 adults in the Upper Colorado River population. The overall average of the six adult survival estimates for the two populations (Green and Colorado rivers) was 80%, which is similar to the estimated annual survival rate of adults computed by Gilpin (1993) from length distribution.

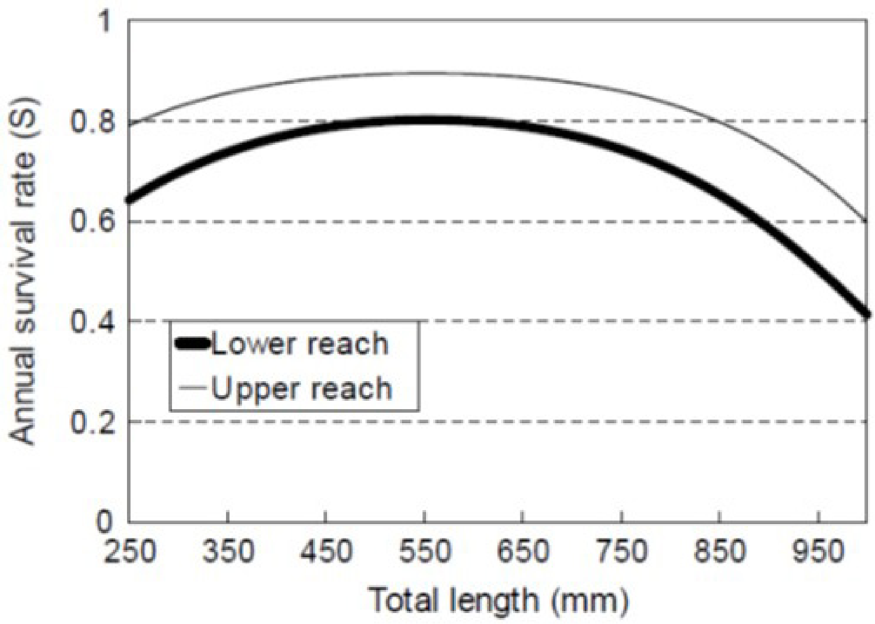

Figure 45. Annual survival rate (S) of Colorado pikeminnow in the Upper Colorado River as a function of fish total length and reach based on model with constant survival. 1991-2005. (Fig. 4 from Osmundson and White 2009).

Overwinter survival of age-0 fish in the Upper Colorado River ranged 7–77% (mean, 49%; McAda and Ryel 1999). Overwinter survival of age-0 Colorado Pikeminnow in Green River backwaters, based on mark-recapture population estimates, ranged 6–62% (mean, 45%), compared to catch rate estimates for the same period of 11–49% (mean, 34%; Haines et al. 1998).

18.3 San Juan River Subbasin

Estimated survival of Colorado Pikeminnow for ages 1−3 were determined from changes in mark-recapture abundance estimates of stocked fish (Figure 46, Table 22). These survival estimates are based on the time interval from stocking in late summer/fall to the next census 1 year later; whereas survival rates presented in Table 23 are for a different interval of time for wild fish of the Green and Upper Colorado rivers.

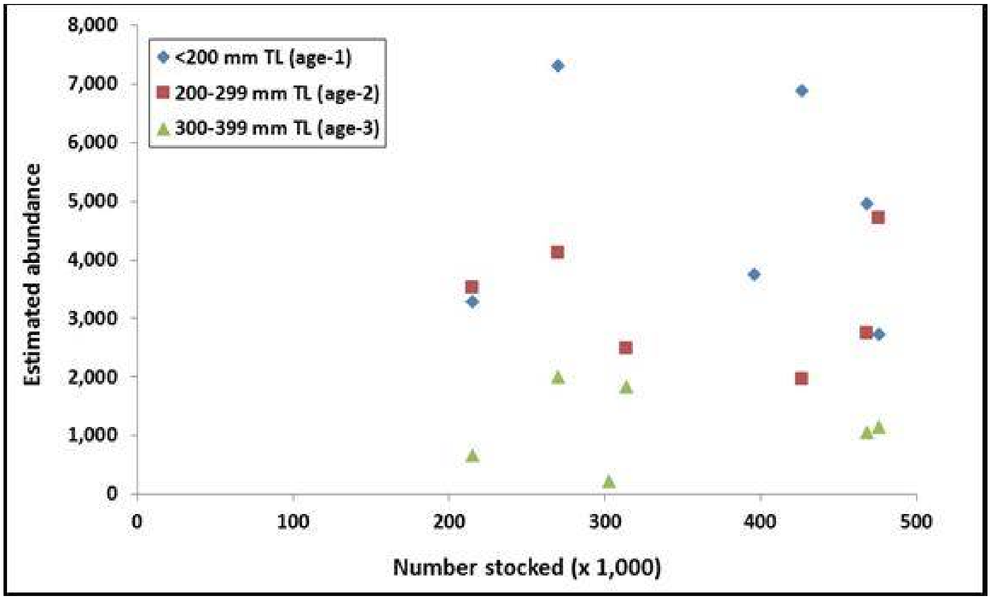

Figure 46. Estimated abundance of age-1, age-2, and age-3 Colorado Pikeminnow after having been stocked in the San Juan River at age-0. Figure provided by Scott Durst (USFWS).

Table 22. Estimated survival of Colorado Pikeminnow in the San Juan River based on mark-recapture abundance estimates from stocking at age-0 to ages 1−3. Data and analysis provided by Scott Durst (USFWS).

Statistic	Age-0 to Age-1	Age-1 to Age-2	Age-1 to Age-2	Age-2 to Age-3
Mean	0.014	0.841	0.467	0.409
SD	0.007	0.573	0.157	0.217
CV	0.531	0.682	0.336	0.53

18.4 Summary of Survival Estimates

The following is a breakdown of survival rates for eggs and age-0 fish.

Eggs and Age 0.—Estimates of egg survival were determined from Hamman (1986) in which he injected and manually striped hatchery-reared 9 and 10-year old fish at Willow Beach National Fish Hatchery. The eggs were held at 22ºC in Heath trays or jars, and the number of viable eggs enumerated after 48 hr of the stated 100-hr incubation period. Estimates of egg survival were computed by expanding the 48-hr viability counts to estimated viability after 100 hr of incubation (to hatching). Estimated survival of eggs was 0.3145.

Age 0, Phase a (7 d hatch to swim-up).—Survival was estimated as the numbers of larvae counted by Hamman (1986) 5-7 days after hatching, or at the time of swim-up, compared to the number of viable eggs after 100 hr of incubation.

Age 0, Phase b (50 d post-swim-up).—Survival was estimated as the numbers of larvae surviving in outdoor earthen ponds 50 days after swim-up (Hamman 1989). These fish were 57 days of age (i.e., 7 days from hatch to swim-up + 50 days in the ponds). Daily survival was computed for fish held in each of three separate ponds (48, 49, and 51 days), and average survival was computed for a standardized period of 50 days.

Age 0, Phase c (90 d post-swim-up).—Survival was estimated as the numbers of larvae surviving in outdoor earthen ponds from day 51 to day 90 following swim-up (Hamman 1989). These fish were 58-97 days of age (i.e., 57 days from hatching + 40 days in the ponds). Daily survival was computed for fish held in each of two separate ponds (36 and 40 days), and average survival was computed for a standardized period of 40 days.

Age 0, Phase d (6 mo overwinter survival).—Survival was estimated as the numbers of young surviving in natural backwaters of the Green and Upper Colorado rivers from October 1 to March 31 (Valdez and Cowdell 1996). These fish were 98-278 days of age. Survival for the period between collections was computed from catch-per-effort (CPE) of fish seined in backwaters in fall and in the following spring (backwaters remained open to the river without confinement to fish movement). Daily survival was computed for each of 7–9 years, standardized for 6 months and averaged.

Age 0, Phase e (3 mo post-winter survival).—Survival was estimated from the monthly survival computed from catch rates of young in natural backwaters of the Green and Upper Colorado rivers (Valdez and Cowdell 1996) and applied to the period April 1 to June 3. This may be an underestimate of survival because it is based on the winter period when survival is believed to be low; nevertheless, this period encompasses the spring runoff, when flows are high and fish are being displaced from habitats and exposed to predators and possibly food shortages. These fish were 279 – 365 days old.

Cumulative survival of age-0 fish for phases a-e was 0.0314.

18.5 Summary of Survival Estimates

The following Table 23 is a breakdown of survival rates for ages 1-7+, based on annual CPUE (From Excel spreadsheet provided by K. Bestgen, Pers. Comm., 2016).

Table 23. Estimated survival rate by age for Colorado Pikeminnow in the Green River. From Excel spreadsheet provided by K. Bestgen (Pers. Comm., 2016).

Parameter	Age-1	Age-2	Age-3	Age-4	Age-5	Age-6	Age7+
Survival (S)	0.21	0.31	0.41	0.51	0.62	0.72	0.82
Mortality (1-S)	0.79	0.69	0.59	0.49	0.38	0.28	0.18

The following Table 24 summarizes the mortality rates by age for the Colorado Pikeminnow in the Green River, Upper Colorado River, and San Juan River subbasins.

Table 24. Mortality of Colorado Pikeminnow by age for the Green River, Upper Colorado River, and San Juan River subbasins. Estimates of mortality (1-Survival) are computed from Figures 45 and 46 and from Tables 20, 21, and 22.

Age	Green River	Upper Colorado River	San Juan River
Eggs	0.69	0.69	0.69
0 – 1	0.97	0.97	0.97
1 – 2	0.79	0.69	0.16
2 – 3	0.69	0.61	0.59
3 – 4	0.59	0.53	--
4 – 5	0.49	0.45	--
5 – 6	0.38	0.36	--
6 – 7	0.28	0.27	--
Adult (7+)	0.18	0.15	--

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Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

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IUCN SSC Conservation Planning Specialist Group

In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

2. Miller, P.S. 2017. Summary of statistics for retrospective analysis of Colorado pikeminnow abundance in the Green and Upper Colorado River subbasins.

Summary of statistics for retrospective analysis of Colorado pikeminnow abundance in the Green and Upper Colorado River subbasins.

1. Green River Subbasin, Dual-Phase Dynamic: 1991-2000

Nonlinear Regression **Thursday, August 25, 2016, 3:22:08 PM**

Data Source: Green River Data in CPM_VortexAnalysis
Equation: Exponential Growth, Single, 2 Parameter
f=a*exp(b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9165	0.8399	0.8199	162.6837

Coefficient		Std. Error	t	P
a	2906.820	89.2792	32.5588	<0.0001
b	0.0342	0.0053	6.4639	0.0002

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	117202447.1648	58601223.5824
Residual	8	211727.9414	26465.9927
Total	10	117414175.1062	11741417.5106

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	1110719.9711	1110719.9711	41.9678	0.0002
Residual	8	211727.9414	26465.9927		
Total	9	1322447.9125	146938.6569		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.7590)

W Statistic= 0.9577 Significance Level = 0.0500

Constant Variance Test Failed (P = 0.0377)

Fit Equation Description:

```
[Variables]
x = col(9)
y = col(11)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=ape(x,ln(y),1,0,1)
[Parameters]
a = exp(F(0)[1]) ''Auto {{previous: 2906.82}}
b = F(0)[2] ''Auto {{previous: 0.0342173}}
[Equation]
f=a*exp(b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
```

```
[Constraints]
b>0
[Options]
tolerance=1e-10
stepsize=1
iterations=200

Number of Iterations Performed = 7
```

2. Green River Subbasin, Dual-Phase Dynamic: 2000-2013

Nonlinear Regression **Thursday, August 25, 2016, 3:25:22 PM**

Data Source: Green River Data in CPM_VortexAnalysis
Equation: Exponential Decay, Single, 2 Parameter
f = a*exp(-b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.9454	0.8937	0.8804	273.4427

Coefficient		Std. Error	t	P
a	6640.6355	672.8957	9.8687	<0.0001
b	0.0575	0.0074	7.8181	<0.0001

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	86090069.7303	43045034.8652
Residual	8	598167.2697	74770.9087
Total	10	86688237.0000	8668823.7000

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	5030285.6303	5030285.6303	67.2760	<0.0001
Residual	8	598167.2697	74770.9087		
Total	9	5628452.9000	625383.6556		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.5276)

W Statistic= 0.9377 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3270)

Fit Equation Description:

```
[Variables]
x = col(9)
y = col(12)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=if(size(x)>1, if(total(abs(y))>0, ape(x,log(abs(y)),1,0,1), -306), 0)
asign(q)=if(mean(q)>=0,1,-1)
```

```
[Parameters]
a = if(F(0)[1]< 307, if(F(0)[1]>-307, asign(y)*10^F(0)[1], asign(y)*10^(-307)),
asign(y)*10^307) ''Auto {{previous: 6640.64}} {{MinRange: -3}} {{MaxRange: 9}}
b = if(x50(x,y)-min(x)=0, 1,  -ln(.5)/(x50(x,y)-min(x)))  ''Auto {{previous:
0.0575248}} {{MinRange: 0}} {{MaxRange: 1}}
[Equation]
f = a*exp(-b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
[Constraints]
b>0
[Options]
tolerance=1e-10
stepsize=1
iterations=200

Number of Iterations Performed = 9
```

3. Green River Subbasin, Single-Phase Dynamic: 1991-2013

Nonlinear Regression **Friday, August 25, 2017, 12:09:08 PM**

Data Source: Green River Data in CPM_VortexAnalysis.JNB
Equation: Exponential Decay, Single, 2 Parameter
f = a*exp(-b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.5970	0.3564	0.3185	534.6265

	Coefficient	Std. Error	t	P
a	3636.2614	238.0799	15.2733	<0.0001
b	0.0174	0.0062	2.8139	0.0120

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	182539809.4296	91269904.7148
Residual	17	4859033.6766	285825.5104
Total	19	187398843.1062	9863097.0056

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	2690781.1451	2690781.1451	9.4141	0.0070
Residual	17	4859033.6766	285825.5104		
Total	18	7549814.8217	419434.1568		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.4217)

W Statistic= 0.9517 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.6256)

Fit Equation Description:

```
[Variables]
x = col(9)
y = col(10)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=if(size(x)>1, if(total(abs(y))>0, ape(x,log(abs(y)),1,0,1), -306), 0)
asign(q)=if(mean(q)>=0,1,-1)
[Parameters]
a = if(F(0)[1]< 307, if(F(0)[1]>-307, asign(y)*10^F(0)[1], asign(y)*10^(-307)),
asign(y)*10^307) ''Auto {{previous: 3636.26}} {{MinRange: -3}} {{MaxRange: 9}}
b = if(x50(x,y)-min(x)=0, 1,  -ln(.5)/(x50(x,y)-min(x)))  ''Auto {{previous:
0.017398}} {{MinRange: 0}} {{MaxRange: 1}}
[Equation]
f = a*exp(-b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
[Constraints]
b>0
[Options]
tolerance=1e-10
stepsize=1
iterations=200
```

Number of Iterations Performed = 7

4. Upper Colorado River Subbasin, Dual-Phase Dynamic: 1992-2005

Nonlinear Regression **Thursday, August 25, 2016, 2:33:28 PM**

Data Source: Colorado River Data in CPM_VortexAnalysis
Equation: Exponential Growth, Single, 2 Parameter
f=a*exp(b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.5889	0.3468	0.2535	107.0572

	Coefficient	Std. Error	t	P
a	580.6989	60.0416	9.6716	<0.0001
b	0.0224	0.0118	1.9068	0.0982

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	4177714.1780	2088857.0890
Residual	7	80228.6409	11461.2344
Total	9	4257942.8189	473104.7577

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	42591.4978	42591.4978	3.7161	0.0952
Residual	7	80228.6409	11461.2344		
Total	8	122820.1388	15352.5173		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.1123)

W Statistic= 0.8664 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3811)

Fit Equation Description:
```
[Variables]
x = col(1)
y = col(4)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=ape(x,ln(y),1,0,1)
[Parameters]
a = exp(F(0)[1]) ''Auto {{previous: 580.699}}
b = F(0)[2] ''Auto {{previous: 0.0224137}}
[Equation]
f=a*exp(b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
[Constraints]
b>0
[Options]
tolerance=1e-10
stepsize=1
iterations=200
```

Number of Iterations Performed = 7

5. Upper Colorado River Subbasin, Dual-Phase Dynamic: 2005-2015

Nonlinear Regression **Thursday, August 25, 2016, 2:40:29 PM**

Data Source: Colorado River Data in CPM_VortexAnalysis
Equation: Exponential Decay, Single, 2 Parameter
f = a*exp(-b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.8866	0.7861	0.7434	95.1552

	Coefficient	Std. Error	t	P
a	2000.0000	679.4829	2.9434	0.0321
b	0.0716	0.0197	3.6435	0.0148

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	2242125.8957	1121062.9479
Residual	5	45272.5605	9054.5121
Total	7	2287398.4562	326771.2080

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	166416.0701	166416.0701	18.3794	0.0078
Residual	5	45272.5605	9054.5121		
Total	6	211688.6305	35281.4384		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.2361)

W Statistic= 0.8821 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.3410)

Fit Equation Description:
```
[Variables]
x = col(1)
y = col(5)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=if(size(x)>1, if(total(abs(y))>0, ape(x,log(abs(y)),1,0,1), -306), 0)
asign(q)=if(mean(q)>=0,1,-1)
[Parameters]
a = if(F(0)[1]< 307, if(F(0)[1]>-307, asign(y)*10^F(0)[1], asign(y)*10^(-307)),
asign(y)*10^307) ''Auto {{previous: 2000}} {{MinRange: -3}} {{MaxRange: 9}}
b = if(x50(x,y)-min(x)=0, 1,  -ln(.5)/(x50(x,y)-min(x)))  ''Auto {{previous:
0.0715984}} {{MinRange: 0}} {{MaxRange: 1}}
[Equation]
f = a*exp(-b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
[Constraints]
b>0
a = 2000
```

```
[Options]
tolerance=1e-10
stepsize=1
iterations=200

Number of Iterations Performed = 8
```

6. Upper Colorado River Subbasin, Single-Phase Dynamic: 1992-2015

Nonlinear Regression **Monday, August 08, 2016, 1:41:18 PM**

Data Source: Colorado River Data in CPM_VortexAnalysis
Equation: Exponential Decay, Single, 2 Parameter
f = a*exp(-b*x)

R	Rsqr	Adj Rsqr	Standard Error of Estimate
0.4173	0.1741	0.1106	143.1641

	Coefficient	Std. Error	t	P
a	696.8858	73.6183	9.4662	<0.0001
b	0.0129	0.0083	1.5526	0.1445

Analysis of Variance:

Analysis of Variance:

	DF	SS	MS
Regression	2	5475180.9566	2737590.4783
Residual	13	266447.4996	20495.9615
Total	15	5741628.4562	382775.2304

Corrected for the mean of the observations:

	DF	SS	MS	F	P
Regression	1	56180.7342	56180.7342	2.7411	0.1217
Residual	13	266447.4996	20495.9615		
Total	14	322628.2338	23044.8738		

Statistical Tests:

Normality Test (Shapiro-Wilk) Passed (P = 0.9131)

W Statistic= 0.9741 Significance Level = 0.0500

Constant Variance Test Passed (P = 0.5315)

Fit Equation Description:

```
[Variables]
x = col(1)
y = col(2)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=if(size(x)>1, if(total(abs(y))>0, ape(x,log(abs(y)),1,0,1), -306), 0)
asign(q)=if(mean(q)>=0,1,-1)
```

```
[Parameters]
a = if(F(0)[1]< 307, if(F(0)[1]>-307, asign(y)*10^F(0)[1], asign(y)*10^(-307)),
asign(y)*10^307) ''Auto {{previous: 696.886}} {{MinRange: -3}} {{MaxRange: 9}}
b = if(x50(x,y)-min(x)=0, 1,  -ln(.5)/(x50(x,y)-min(x)))  ''Auto {{previous:
0.0128708}} {{MinRange: 0}} {{MaxRange: 1}}
[Equation]
f = a*exp(-b*x)
fit f to y
''fit f to y with weight reciprocal_y
''fit f to y with weight reciprocal_ysquare
[Constraints]
b>0
[Options]
tolerance=1e-10
stepsize=1
iterations=200

Number of Iterations Performed = 7
```

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

Philip S. Miller, Ph.D.
Senior Program Officer
IUCN SSC Conservation Planning Specialist Group

In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

3. Miller, P.S. 2017. Consideration of the Dynamics of "Fecundity Spikes" in the Upper Colorado River. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Consideration of the Dynamics of "Fecundity Spikes" in the Upper Colorado River
Phil Miller, IUCN-SSC Conservation Planning Specialist Group
15 September, 2017

1992-2014: Mean Age-0 production for years in which adult abundance estimates are available: 19,002.0 (Bestgen dataset)
Mean estimated Age-0 production per adult female = 78.81 (assuming 82% of adult females successfully spawn, as is assumed in current PVA).

2015: "Fecundity Spike" year
Estimated Age-0 abundance from autumn ISMP sampling = 761,100 (Bestgen dataset)
(40.06 times larger than 1992-2014 mean production)
Estimated number of adults = 429 = 214.5 females (Bestgen dataset)
Estimated Age-0 production per adult female = 761,100 / (214.5*0.82) = 4327 (assuming 82% of adult females successfully spawn, as is assumed in current PVA).

Mortality schedule in current PVA suggests that cumulative survival rate of Colorado pikeminnow from first observation during autumn ISMP sampling (designated Age-0) to recruitment into the adult stage (>450mm TL; designated Age-7) is 0.0047.

Therefore, expected total number of Age-0 individuals produced per successfully spawning adult in the 2015 "fecundity spike" that survive to recruitment in the adult stage = (4327)*(0.0047) = 20.41. (This accounts for 82% spawning success among adult females)

Therefore, given our estimate of 214 adult females in the river in the summer of 2015, we would assume that, after seven years of growth and maturation of fish produced in 2015, approximately (20.41)*[(214)*(0.82)] = 3580 fish would be recruited into the adult cohort for spawning in the summer. (Equivalently: (761,100)*(0.0047) = 3580) This would represent an 8-fold increase in total adult population size (relative to the year in which the spike occurred) when males are included in the calculation.

This conclusion, emerging from the logical argument provided above, may be unrealistic for at least two reasons:

1. Given that the estimated carrying capacity (*K*) for the Upper Colorado River is set at 1000 adults, it is clear the spawning spike observed in 2015 and as considered here would be strongly truncated by *K*. This is indeed happening in the current PVA model (Figure 1). The current value of *K* for the Upper Colorado may be an underestimate and could potentially be increased to 1500 adults or perhaps even higher. However, even with a larger revised estimate for *K*, the demographic consequences of the spawning spike would be significantly attenuated by the ceiling imposed by *K*. On these mechanistic grounds, therefore, the spawning spike as currently simulated in the PVA may be unrealistic. A key assumption in the simulation mechanic is that there is effectively no density-dependent mortality of the individuals comprising the spike; the greatly increased cohort produced by the spawning spike experiences the same level of age-specific mortality as other cohorts produced during more "average" years.

2. We may also look at past population abundance estimates to gauge the magnitude of increases in the number of adults over the recent past. Since 1992, inter-annual abundance increases of 60% (1992-1993), 45% (2013-2014) and 30% (1998-1999 and 2004-2005) have been observed. None of these observations, however, approach the 8-fold increase expected (given our assumptions discussed above) from the 2015 spawning spike discussed above.

As a means of further exploring this dynamic, an extended set of scenarios were constructed that differed only in the intensity of the fecundity spike:

- Full Spike: 4000 Age-0 fish per successful female
- Mid Spike: 2000 Age-0 fish per successful female
- Low Spike: 1000 Age-0 fish per successful female
- Very Low Spike: 500 Age-0 fish per successful female

At this point, only single iterations have been run for each scenario in order to evaluate iteration-specific behavior, while recognizing that these iterations may not fully represent typical population dynamics. Nevertheless, the iteration analysis is instructive for observing the consequences of specific fecundity spikes and their overall realism.

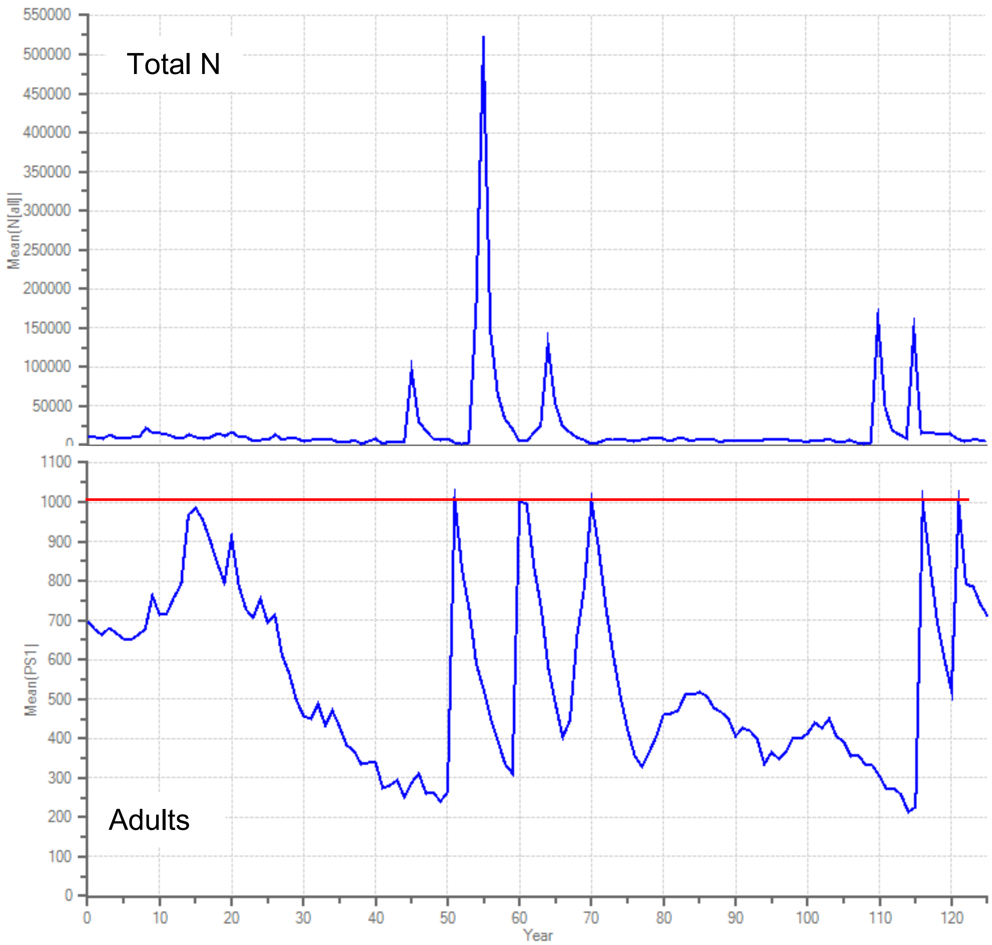
Figures 2 through 5 show results for the Mid Spike, Low Spike and Very Low Spike scenarios. While the spikes remain visible, the reduced intensity of the fecundity spikes is clearly evident in the plots of total population abundance. Both the Mid Spike and Low Spike scenarios show dramatic increases in adult population size across a single year as a result of the identified spawning spikes, with three- to four-fold increases in abundance occurring in multiple years. These increase in abundance would likely be considerably larger if the carrying capacity restriction were lifted.

The Very Low Spike scenario – at least the single iteration show here for illustration – appears to begin to show more realistic population dynamics. Increases of 300-400 individuals are seen in the trajectory, which is more in line with observed increases in the field dataset (e.g., addition of 260 individuals from 1992 to 1993). Moreover, the extreme increases in adult abundance that are subject to significant truncation at carrying capacity appear to be much less evident.

Overall, this preliminary evaluation suggests that explicitly simulating the type of “fecundity spike” first observed in 2015 may overestimate its long-term impact on changes in adult abundance. This is not to say, however, that the event should be removed from the model structure. Instead, a spike with some form of attenuated intensity – perhaps significantly attenuated, based on the results here – may be the best approach.

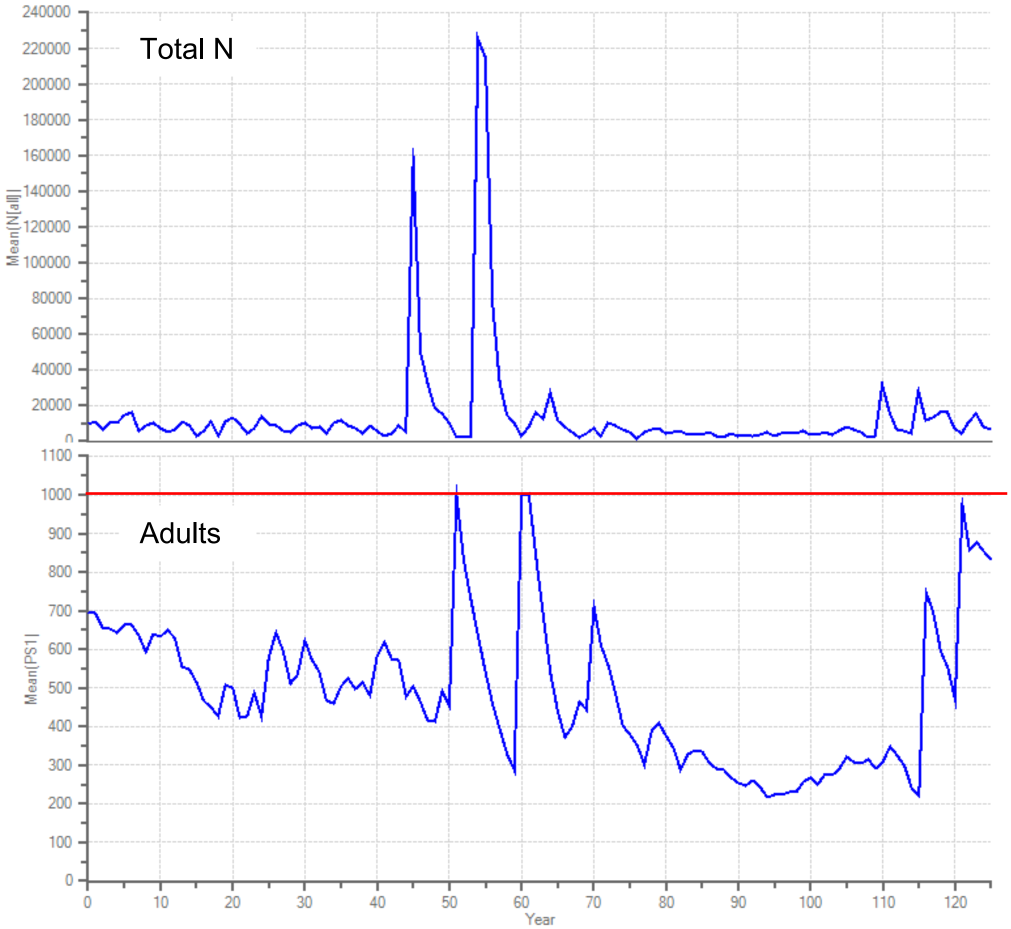
Careful consideration of the likely intensity of the spike, and its longer-term impact on adult population abundance, is important for responsible PVA model construction and interpretation.

Figure 1.FULL SPIKE: Age-0 production = 4000 per successful female



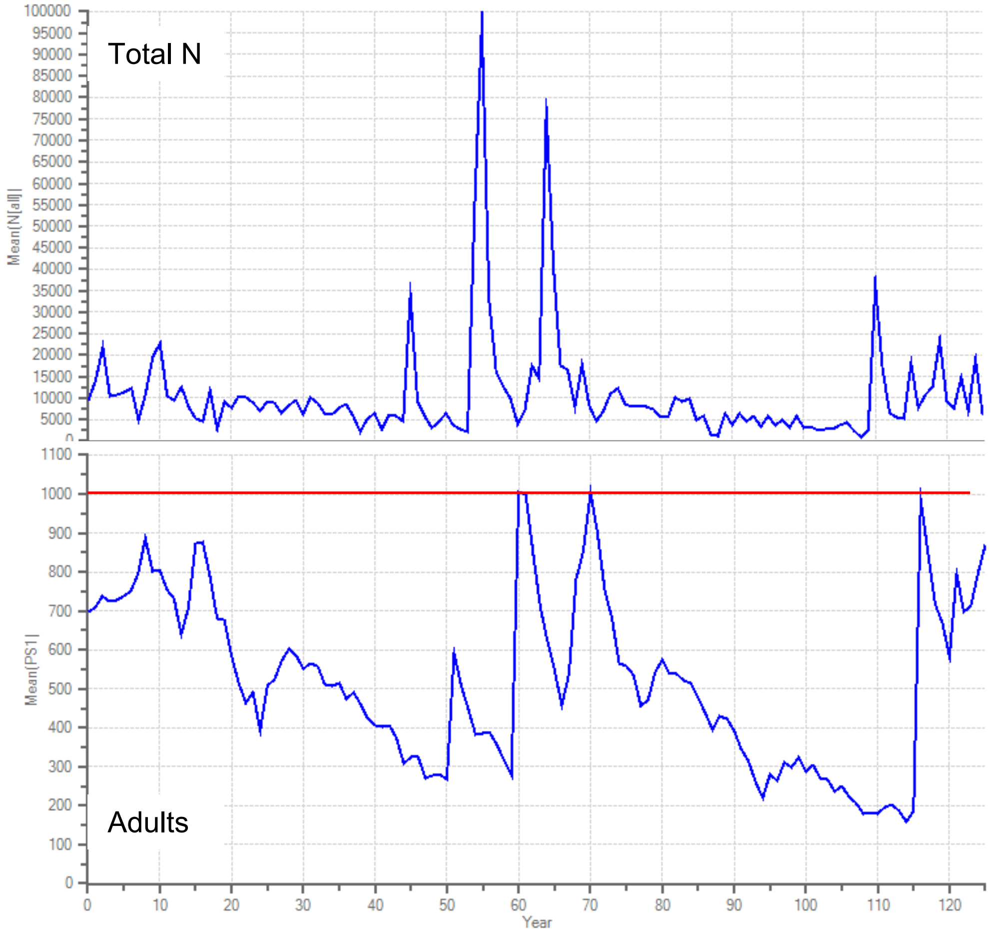
Single trajectory of the Colorado pikeminnow population dynamics model for Upper Colorado River subbasin (single-phase retrospective dynamic). Top panel, total population abundance; bottom panel, adults only. The spikes in total abundance seen in years 45, 55, 65, 110 and 115 are the result of fecundity spikes. Associated increases in adult abundance are evident, with the 7-year lag corresponding to growth and aging of the fish produced in the spike. Horizontal red line in the bottom panel denotes the identified ecological carrying capacity (1000 adults) used in all models to date. Specific demographic dynamics seen in this single iteration may not be representative of the mean outcome observed over 10,000 iterations that comprise the formal PVA.

Figure 2. MID SPIKE: Age-0 production = 2000 per successful female



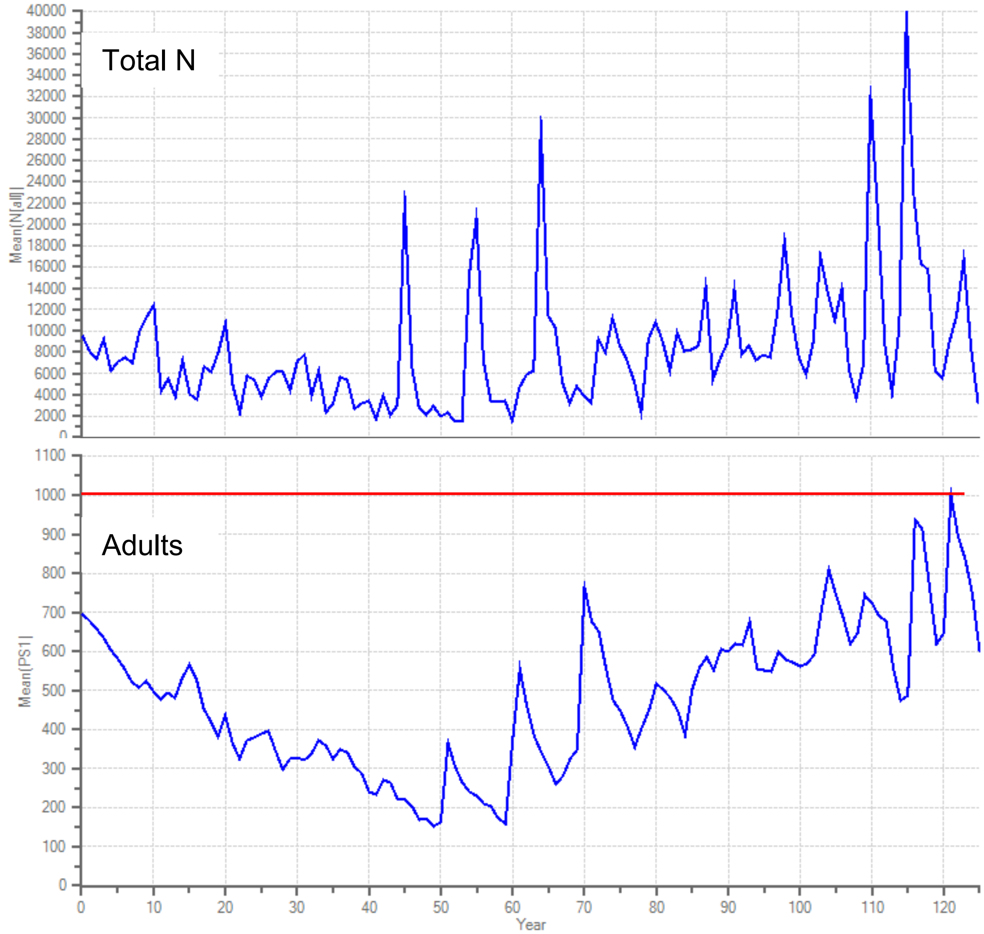
Single trajectory of the Colorado pikeminnow population dynamics model for Upper Colorado River subbasin (single-phase retrospective dynamic). Top panel, total population abundance; bottom panel, adults only. The spikes in total abundance seen in years 45, 55, 65, 110 and 115 are the result of fecundity spikes. Associated increases in adult abundance are evident, with the 7-year lag corresponding to growth and aging of the fish produced in the spike. Horizontal red line in the bottom panel denotes the identified ecological carrying capacity (1000 adults) used in all models to date. Specific demographic dynamics seen in this single iteration may not be representative of the mean outcome observed over 10,000 iterations that comprise the formal PVA.

Figure 3.LOW SPIKE: Age-0 production = 1000 per successful female



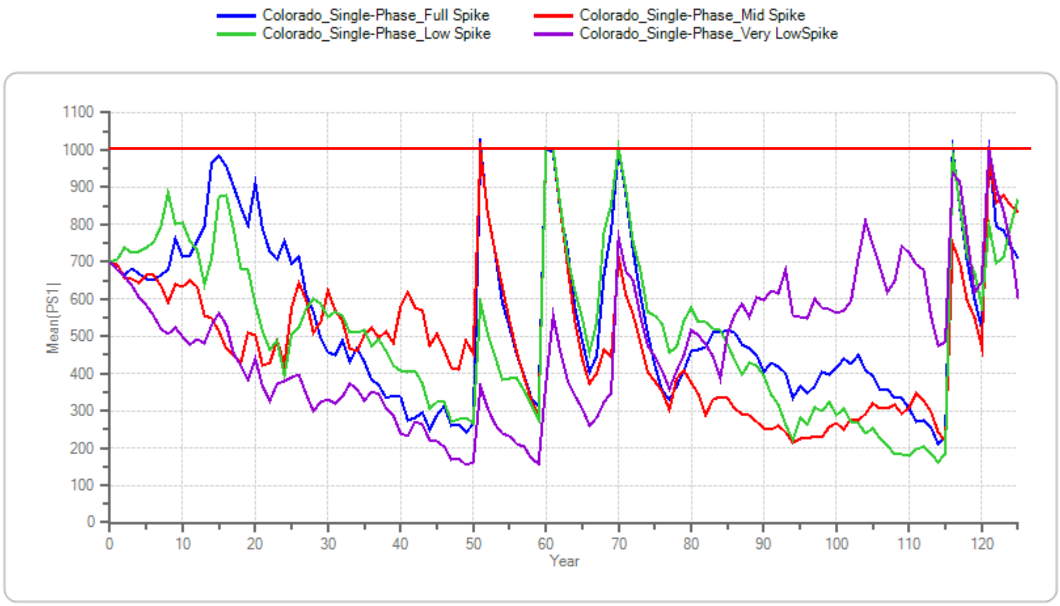
Single trajectory of the Colorado pikeminnow population dynamics model for Upper Colorado River subbasin (single-phase retrospective dynamic). Top panel, total population abundance; bottom panel, adults only. The spikes in total abundance seen in years 45, 55, 65, and 110 are the result of fecundity spikes. Associated increases in adult abundance are evident, with the 7-year lag corresponding to growth and aging of the fish produced in the spike. Horizontal red line in the bottom panel denotes the identified ecological carrying capacity (1000 adults) used in all models to date. Specific demographic dynamics seen in this single iteration may not be representative of the mean outcome observed over 10,000 iterations that comprise the formal PVA.

Figure 4. VERY LOW SPIKE: Age-0 production = 500 per successful female



Single trajectory of the Colorado pikeminnow population dynamics model for Upper Colorado River subbasin (single-phase retrospective dynamic). Top panel, total population abundance; bottom panel, adults only. The spikes in total abundance seen in years 45, 55, 65, 110 and 115 are the result of fecundity spikes. Associated increases in adult abundance are evident, with the 7-year lag corresponding to growth and aging of the fish produced in the spike. Horizontal red line in the bottom panel denotes the identified ecological carrying capacity (1000 adults) used in all models to date. Specific demographic dynamics seen in this single iteration may not be representative of the mean outcome observed over 10,000 iterations that comprise the formal PVA.

Figure 5. SUMMARY: ADULT POPULATION RESPONSE



Summary of single trajectories of the Colorado pikeminnow population dynamics model for Upper Colorado River subbasin (single-phase retrospective dynamic). The plot shows adult abundance for each of the four fecundity spike scenarios (see legend). Horizontal red line denotes the identified ecological carrying capacity (1000 adults) used in all models to date.

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

Philip S. Miller, Ph.D.
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SUPPORTING INFORMATION

4. McAbee, K. 2017a. Incorporating Recovery Program conservation actions in the PVA modeling framework: Multiple test cases. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Incorporating Recovery Program Conservation Actions into the PVA Modeling Framework: Multiple Test Cases

Kevin McAbee, Upper Colorado River Recovery Program

Flow regimes and nonnative fish are two primary factors which affect Colorado pikeminnow demographic rates, such as survival of various life stages, carrying capacity, and reproduction potential. Unfortunately, because of complex interactions of ecological conditions, it is challenging to quantify relationships between various flow regimes or nonnative fish and specific population demographics of Colorado pikeminnow. However, when data from long term monitoring or other empirical research is available, those data can be used to investigate the relationship between specific ecological conditions and certain demographic rates. Then, those demographic rates can be adjusted within a PVA to determine the sensitivity of Colorado pikeminnow populations to certain management actions that impact the ecological conditions.

This white paper proposes to use the existing PVA to investigate Colorado pikeminnow population response in the Green River sub-basin to future management actions which are being implemented, or planned with high level of certainty. The management actions proposed, and the resultant population demographic changes, are:

1. Providing elevated summer base flows regimes, which should increase production of age-0 Colorado pikeminnow;
    a. Mean annual age-0 Colorado pikeminnow production for both the middle Green and lower Green River nursery areas would be increased by 55% and 14% respectively, based on analysis of long-term fall monitoring and revised flow regimes.
2. Removing large bodied nonnative predatory fishes, specifically northern pike, walleye, and smallmouth bass, which should increase Colorado pikeminnow carrying capacity;
    a. Carrying capacity of the Green River sub-basin would be increased from 4200 to 6000 (incrementally) to represent increased niche space of nonnative fish removal.
3. Removing smallmouth bass and walleye in Colorado pikeminnow nursery areas, which should increase survival of age-1 to age-5 fish;
    a. Survival rates of Colorado pikeminnow from age-0 to sub-adult stages (~300 mm) would be increased (incrementally) by a factors of 5% up to 20% to represent successful nonnative fish suppression in nursery areas.
4. Installation of a weir wall and screen at the intake of a large canal just downstream of a primary Colorado pikeminnow spawning bar, which should increase adult survival by reducing entrainment mortality on individuals that migrate past the diversion during spawning behaviors;
    a. Adult survival in the Green River subbasin would be increased by 1% to represent prevention of entrainment into a problematic irrigation canal.

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Scenario 1: Increased age-0 Colorado pikeminnow production via summer base flow management

Recruitment is a key population rate for species viability, especially in long lived species such as the Colorado pikeminnow. A critical component of the recruitment rate of Colorado pikeminnow is over-summer survival during the first year of life. That is, the majority of Colorado pikeminnow in the larval stage do not survive into the first autumn of life, which is called an age-0 fish.

Bestgen and Hill (2015) demonstrate that production of age-0 Colorado pikeminnow declined in the Green River since 1994 (Bestgen and Hill 2015; Figure 16 below). The authors further demonstrate that declines in summer base flow magnitude (Figure 17 below) were correlated with declining densities of age-0 Colorado pikeminnow in both the middle and lower Green River. Declines in age-0 production undoubtedly factor heavily into recent reduced adult abundance estimates.

In order to improve the production of age-0 Colorado pikeminnow, Bestgen and Hill (2015) recommend implementing elevated summer base flows; specifically, base flows between 1700- 3000 cfs in the middle Green River, and 1700-3800 cfs in the lower Green River (Bestgen and Hill 2015; Figure 18). Figure 18 shows high densities of age-0 Colorado pikeminnow during these flow regimes when backwater habitats are available in which to grow.

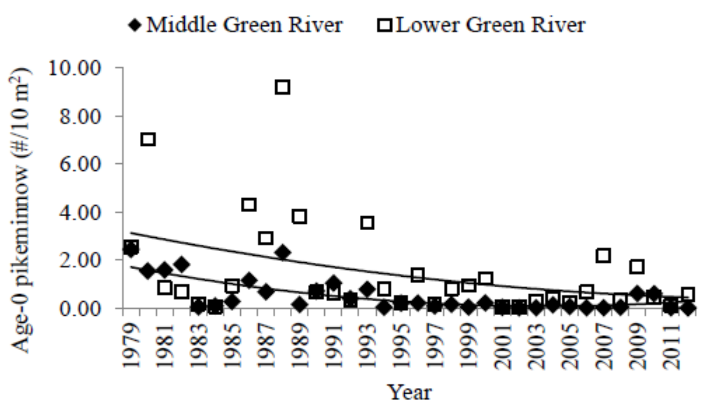

Figure 16. Mean annual density of age-0 Colorado pikeminnow captured in backwaters of the middle and lower Green River, 1979-2012. Density is number of pikeminnow captured in backwaters in the area swept by a seine.

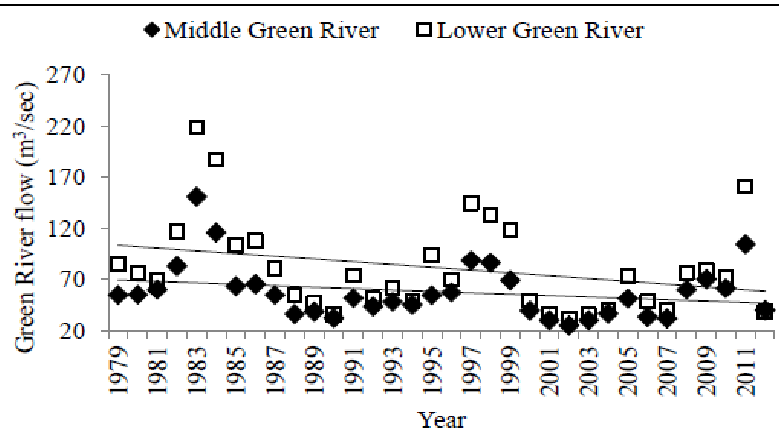

Figure 17. Mean August-September base flow of the middle (Gauge # 09261000) and lower Green River (Gauge # 09315000) reaches, Utah.

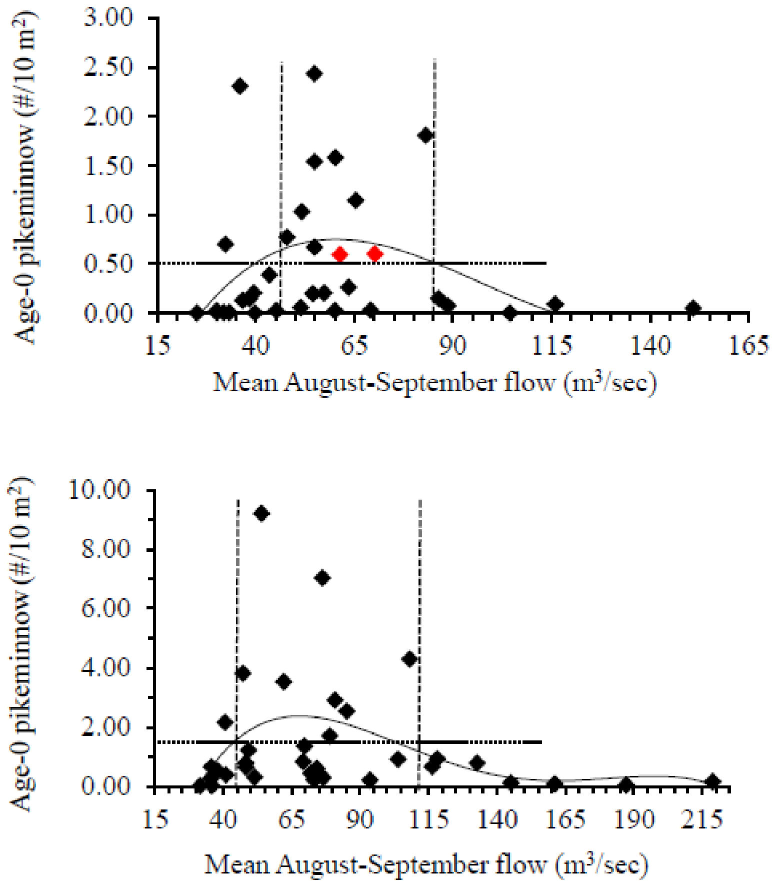

Figure 18. Mean annual density of age-0 Colorado pikeminnow captured in backwaters of the middle (upper panel) and lower (lower panel) Green River as a function of mean August-September flow, 1979-2012. Density is number of pikeminnow captured in area of backwaters swept by a seine. The middle Green River 2009 and 2010 data are red triangles. Dashed vertical lines encompass the flow ranges in each reach when the proportion of above average recruitment years is highest, and the horizontal dotted line is the mean density for the period of record. Polynomial regression relationships illustrate the dome-shaped nature of the recruitment relationship at intermediate flow levels. Green River flows were measured at the Jensen, Utah gauge (09261000) for the middle Green River reach and at the Green River, Utah gauge (09315000) for the lower Green River reach.

Flow releases from Flaming Gorge can be combined with unregulated Yampa River flows to provide these recommended flow regimes to support age-0 production throughout the Green River. Elevated summer base flows to correspond to revised flow recommendations were initially implemented in 2015, with very positive results – preliminary collections of age-0 Colorado pikeminnow from 2015 indicate successful reproduction and late summer survival, widespread occupation of backwater habitats throughout sampling reaches, and capture of several hundred individuals (Breen et al. 2015). While multiple years of recommended conditions would be needed to fully evaluate population response in the wild, this evaluation can be modeled within a PVA (Miller et al. in draft).

Current PVA model predictions are based on historical population trends of Colorado pikeminnow as documented in the wild, which appropriately models the current condition of the species. To evaluate a potential population response to improving base flow conditions, a new distribution of age-0 production parameters can modeled within the PVA. The new dataset should include past years with mean August and September flows within the recommended flow regimes, and the corresponding Colorado pikeminnow production. By doing so, the revised PVA can be evaluated using empirical field data collected during years that meet a pre-defined criteria.

The new input dataset of years that meet recommended elevated base flows (columns 3 and 5 in Table 1) represent an increase in the mean age-0 pikeminnow production in the middle Green of 55% compared to all years since 1979 (column 3 is 55% more than column 2). In the lower Green River, production increases 14% (column 5 is 14% more than column 4). That is, based on past data collected in the field, elevated summer base flows produce a substantially higher mean abundance of age-0 Colorado pikeminnow.

Inputting this data into the PVA will provide an understanding of what this increased production would mean to the long-term abundance of the species in the Green River subbasin.

Table 1. Age-0 Colorado pikeminnow production under differing flow regimes. Frequencies are based on ISMP data collected in the middle and lower Green River and can be found in the Appendix. Columns 2 & 4 represent the existing inputs into the Colorado pikeminnow PVA analysis (Miller et al.). Columns 3 & 5 represent a revised input dataset that represent revised Green River flow implementation, which has been implemented since 2015.

	Middle Green age-0 production		Lower Green age-0 production	
	Existing PVA input: 1979-2015 (complete)	Revised PVA input: 1979-2015 (flows >1700 & <3000 cfs)	Existing PVA input: 1979-2015 (complete)	Revised PVA input: 1979-2015 (flows >1700 & <3800 cfs)
Mean	30,156.42	46,614.47	63,125.67	71,757.42
Standard Deviation	40,715.79	43,559.13	87,623.26	78,244.43

Long term monitoring data and frequency of flows

> To evaluate a potential population response to improving base flow conditions, age-0 production from previous years with flows that meet the revised summer base flow recommendations should be used.

Long-term data sets show the frequency of Green River flow regimes meeting the needs of age-0 pikeminnow has decreased (Table 2). Current adult abundance estimates for Colorado pikeminnow in the Green River show an apparent decline since about 2000 (Bestgen 2010; Bestgen 2016 in draft). Adult populations now are defined by pikeminnow produced in the early portions of the 2000s because Colorado pikeminnow reach sexually maturity at 7-10 years. Therefore, age-0 individuals produced from 2000 to 2007 would be entering into sexually maturity between 2007 and 2017. The flow regimes of the Green River from 2000 to 2007 (inclusive) show a single mean August to September base flow above 1700 cfs in the middle Green River (2005; mean flow = 1813 cfs), and only three years in the lower Green River (2000, 2005, and 2006; mean base flows 1739, 2579, and 1703 respectively). Adult Colorado pikeminnow abundance estimates from 2006-2008 & 2010-2013 show a marked decline in the Green River population, likely heavily influenced by the impacts of low flow regimes from the early 2000s.

In contrast, between 1979 and 1987, flow regimes in the Middle Green River met the proposed criteria of 1700-3000 cfs 77% of those years, with only 1983 and 1984 greatly exceeding the threshold during historically high flow years. In the lower Green River, 1982 also exceeded the threshold, for an overall frequency of 66% in the first 9 years of implementation. Colorado pikeminnow produced from 1979 to 1987 would be expected to reach adulthood from 1986 to 1997, which corresponds to the trend of increasing populations in the 1990s and a large overall abundance estimate in the late 1990s.

Table 2. Frequency that flows in the middle and lower Green River met the revised recommendations of Bestgen & Hill (2016).

Period of Interest	Total Years	Frequency meeting the Bestgen and Hill flow recommendations	
		Middle Green River (base flows >1700 & <3000 cfs)	Lower Green River (base flows >1700 & <3800 cfs)
Since inception of age-0 monitoring program (1979-2015)	37 years	46% (17 of 37)	51% (19 of 37)
1994-2015	22 years	41% (9 of 22)	45% (10 of 22)
Drought period (2000 to 2007)	8 years	16% (1 of 8)	37.5% (3 of 8)
Since Implementation of Muth et al. Flow Recommendations (2005-2015)	11 years	55% (6 of 11)	64% (7 of 11)

Three flow regime scenarios for the Green River Recovery Unit can be modeled:

1. Flow conditions since 1979, which support the YOY data in Bestgen and Hill;
2. Ideal (all years meet the Bestgen and Hill recommendations),
3. Constrained (8 of 10 years meet Bestgen and Hill recommendations).

Justification for modeling this Management Action

Modeling a future in which the Green River is managed for the elevated summer base flow recommendations at a higher frequency is only logical if the management action can be undertaken. Since 2005, flows have met the Bestgen and Hill criteria 54% of the time in the middle Green and 64% of the time in the lower Green (Table 2) which is a testament to improved management of the Green River flow regime.

Since Bestgen and Hill suggested updated base flow recommendations, the Flaming Gorge Technical Working Group has suggested an experimental implementation of modified releases from Flaming Gorge to support a flow between 1700 and 3000 cfs at the Jensen gage which have been implemented in both 2015 and 2016. Implementation has primarily occurred by choosing a flow target at the Jensen gage (for example, 2400 cfs), monitoring the unregulated Yampa flow throughout the summer, and releasing flows from Flaming Gorge to complement Yampa flows and meet the flow target. USBR has shown the capacity and willingness to implement these flows.

Because it is unlikely that USBR will be able to meet these recommendations every year (for operational and hydrological reasons) modeling a scenario in which flows meet the recommendations in 8 out of 10 years and 2 out of 10 years the flows exceed 3000 cfs or are below 1700 cfs (with concurrent low production of age-0 pikeminnow) is useful. This could be considered a “constrained model”.

Summary of flow management scenario

Revised summer base flow scenarios should be modeled as a means to test the potential positive impact that revised flow regimes in the Green River could have on future Colorado pikeminnow adult populations. These scenarios would represent a realistic management action that Recovery Program stakeholders could take to halt the decline of this long lived species. Furthermore, the results of these scenarios could be used as support for implementing the revised flow regimes.

Scenario 2: Increased carrying capacity via reduced large nonnative fish

Large bodied, nonnative fish species greatly alter the ecosystem of the Colorado River basin upstream of Lake Powell. Populations of northern pike, smallmouth bass, and walleye exist in almost every river mile occupied by Colorado pikeminnow in the Green and Colorado Rivers. Northern pike are the most dense in the upper portions of the Yampa and Green rivers, where stream temperatures are colder and shoreline habitats are more vegetated. Pike are found in lower densities in the middle Green River and portions of the upper Colorado River. Smallmouth bass populations overlap with the lower terminus of northern pike presence and continue downstream into warmer habitats, especially occupying nearshore rocky habitats which are abundant in the lower Yampa, middle Green, upper White, and upper Colorado River. Walleye are recent emigrants into the Green and Colorado subbasins, occupying alluvial reaches that are used as nursery habitats by young Colorado pikeminnow, most notably the lower portions of the Green and Colorado rivers, and the middle Green River between Ouray National Wildlife Refuge and Dinosaur National Monument.

Northern pike and smallmouth bass have established large, self-sustaining populations since increases in the early 1990s. Smallmouth bass reproduction is most successful in lower flow, warmer water years. Longer, warmer growing seasons are provided by lower flows, which permits smallmouth bass to grow to lengths that support over winter survival. Northern pike reproduction is closely linked to access to vegetated backwaters in the Yampa River immediately after ice-off. Walleye populations are hypothesized to be supported primarily from reservoir emigration from locations such as Starvation and Red Fleet Reservoirs (downstream escapement through dams) in the middle Green River and Lake Powell in the lower Colorado and Green rivers (upstream migration into riverine habitats). While larval walleye have been documented, and spawning aggregation discovered, no have been signs of walleye recruitment in riverine habitats.

These three large bodied piscivores have serious and multifaceted impacts on native fish populations through predation and competition. As Breton et al. reported in 2015:

> “The predatory threat of large-bodied piscivorous taxa such as northern pike and smallmouth bass is substantial. For example, based on results of a bioenergetics model, Johnson et al. (2008) ranked smallmouth bass as the most problematic invasive species because of their high abundance, habitat use that overlaps with most native fishes, and ability to consume a wide variety of life stages of native fishes in the Colorado River Basin. Increasing populations of piscivores such as smallmouth bass are a major impediment to conservation actions aimed at recovery efforts for the four endangered fishes in the Upper Colorado River Basin: Colorado pikeminnow *Ptychocheilus lucius*”

Newly produced age-0 Colorado pikeminnow are at risk from walleye and smallmouth bass predation in alluvial reaches in their first summer of life; this predation includes northern pike once juvenile fish begin emigrating into upstream areas inhabited by northern pike. In fact, predation risk continues for years until they reach sub adult life stages and substantial body sizes. Large northern pike and walleye can consume juvenile and subadult Colorado pikeminnow, as both species have substantial gape size. To reach sexual maturity at ages 7 to 10 years old, and lengths approximating 450 millimeters (mm), young Colorado pikeminnow must avoid predation in diverse habitats, from multiple skilled predators, over a period of many years.

Additionally, because Colorado pikeminnow are the native apex predator of the Colorado River system, they compete directly with large-bodied nonnative piscivores. Limited food resources can impact population dynamics of predator species both via reduced mean body mass (individual condition) or via reduced number of supported organisms (reduced carrying capacity) (McGarvey et al. 2010; Johnston & McGarvey 2011). Data collected for Colorado pikeminnow and nonnative predators demonstrate that adult Colorado pikeminnow appear highly vulnerable to trophic replacement, especially in locations like the Yampa River where densities of adult nonnative predators are substantial (Martinez 2012). Furthermore, Martinez (2012) concluded that difference between carrying capacity and minimum viable population size was low for Colorado pikeminnow, making it especially at risk for dramatic population declines via resource competition.

Martinez (2012) estimates the historical carrying capacity of Colorado pikeminnow in the Green River Recovery Unit as 3,000 to 4,500 adult fish (5.1 to 7.7 fish per mile) However, recent adult abundance estimates for Colorado pikeminnow in the Green River is substantially less than carrying capacity, with simultaneously elevated catches of nonnative predators. For example, walleye catches in the Green River were nominal prior to about 2008, but "were more than twice as abundant as adult Colorado pikeminnow captured in samples" in 2011 to 2013 (Bestgen et al. in draft 2016). Similarly, in the middle Yampa River, 2012 abundance estimates for northern pike greater than 300mm was 1580 (1069-2482 95% CI; Noble 2015), while abundance estimates of adult Colorado pikeminnow (greater than 450mm) in the same year were only 123 (33-504 95% CI) (Bestgen et al. in draft 2016).

Management Actions to Reduce Nonnative Fish

In response to the impacts of nonnative predators, Recovery Program stakeholders have implemented nonnative species removal actions. Over the past decade, the Recovery Program has enlarged, researched, and improved the effectiveness and efficiency of its removal program. Since the early 2000s, Upper Colorado Program removal activities have expanded from six miles in the Yampa River to over 600 miles in four rivers. Some river reaches are sampled more than a dozen times annually. Comprehensive investigations into the effectiveness of the smallmouth bass and northern pike removal programs (Breton et al. 2015 and Zelakso et al. 2014, respectively) have guided efforts to target disruption of reproduction and to limit escapement from upstream reservoirs. As such, the Recovery Program now focuses on removal of large bodied adults, especially in spawning locations, and the prevention of reservoir escapement via screens, nets, and reservoir reclamation projects. It is important to remember that the phase of the nonnative removal program guided by systematic review has only been implemented for about 5 years.

> Adjusting the carrying capacity of the PVA could model a successful nonnative removal program. Increasing the current carrying capacity from 4200 to 5000, 5500, and 6000 could determine if carrying capacity is an important consideration for species viability

Colorado pikeminnow demographics that currently populate the PVA model represent recent conditions in which nonnative fish flourished. The nonnative removal program was in early development, flows were modified by outdated regimes, and many habitats were not restored. The PVA data assimilation documents indicates that based on body condition and food resources, the apparent carrying capacity of the Green River is 4206 adults (7.4 adults per mile) (Bestgen et al. 2005). These numbers slightly exceed those proposed by Martinez et al. (2012) as carrying capacity for the species in the absence of nonnative species.

Limiting the carrying capacity of a species within a modeling exercise would by definition limit the apparent maximum abundance estimate that population can achieve, which indirectly limits the ability of the modeled population to demonstrate rapid abundance increases from high recruitment years (demographic rebound or plasticity) and increases the likely extinction probability by dampened apparent maximums.

Increasing Carrying Capacity of the Colorado Pikeminnow

Niche space opened through the removal of nonnative fish could substantially increase the viability of Colorado pikeminnow through a concurrent increase in carrying capacity. In order to model successful implementation of a nonnative removal program, the carrying capacity of the system could be adjusted upward in increments of approximately 500 to determine if carrying capacity is a limiting demographic rate for Colorado pikeminnow.

Table 3. Suggested incremental increases in carrying capacity to represent large bodied nonnative fish removal.

Recovery Unit	Current modeled carrying capacity (K)	Revised modeled carrying capacities (K) to evaluate reduced competition from large piscivorous taxa		
Green River	4200	5000	5500	6000

Justification

The current nonnative strategy focuses on removing adult life stages of northern pike, walleye, and smallmouth bass in designated critical habitat reaches for Colorado pikeminnow (and certain upstream areas to prevent downstream emigration). Removal efforts have recently focused on targeting species in spawning conditions to enhance the removal of adults. As a result, the size structure of northern pike and smallmouth populations have shifted towards smaller individuals and an overall reduction in catches of large piscivorous individuals[1]. For example, in the middle Yampa River, reduction in the number of northern pike greater than 450 mm since the inception of backwater netting effort in 2014 (see Figure 6 taken from Noble 2016, below) has occurred. Similarly, catch smallmouth bass greater than 325 mm are rarely captured during typical removal efforts, with catches typically dominated by sizes less than 250 mm (Figure 7 taken from various reports, below).

While this may not necessarily mean a reduction in the capability of these species to persist as self-sustaining populations, it does reduce the effects of competition at the highest trophic levels. As a result, this should result in a steadily increasing carrying capacity for adult Colorado pikeminnow.

[1] Martinez (2012) estimated that a 450 mm northern pike, a 325 mm smallmouth bass, and a 375 mm walleye is the biomass equivalent of an adult Colorado pikeminnow (450 mm).

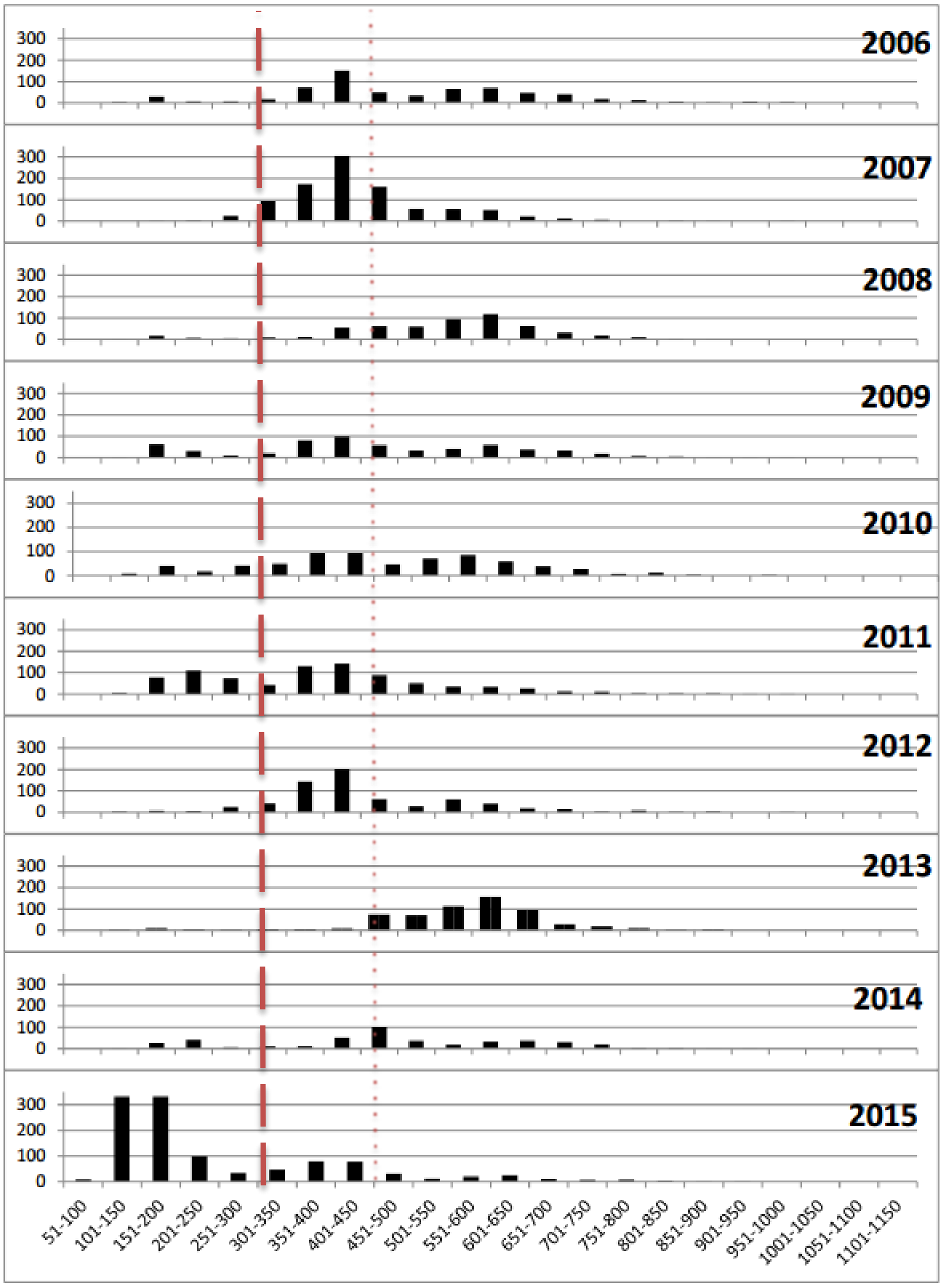

Figure 6. Northern pike size structure in the middle Yampa River as presented by Noble (2015). Dotted vertical line represents 450 mm, indicating a direct competitor to adult Colorado pikeminnow. Dashed vertical line indicates 300mm, or the demarcation of adult northern pike. Note the shift in size structure from adult fish in 2009 to 2012 to very large adults in 2013 and the dramatic reduction in adult and large adults in 2014.

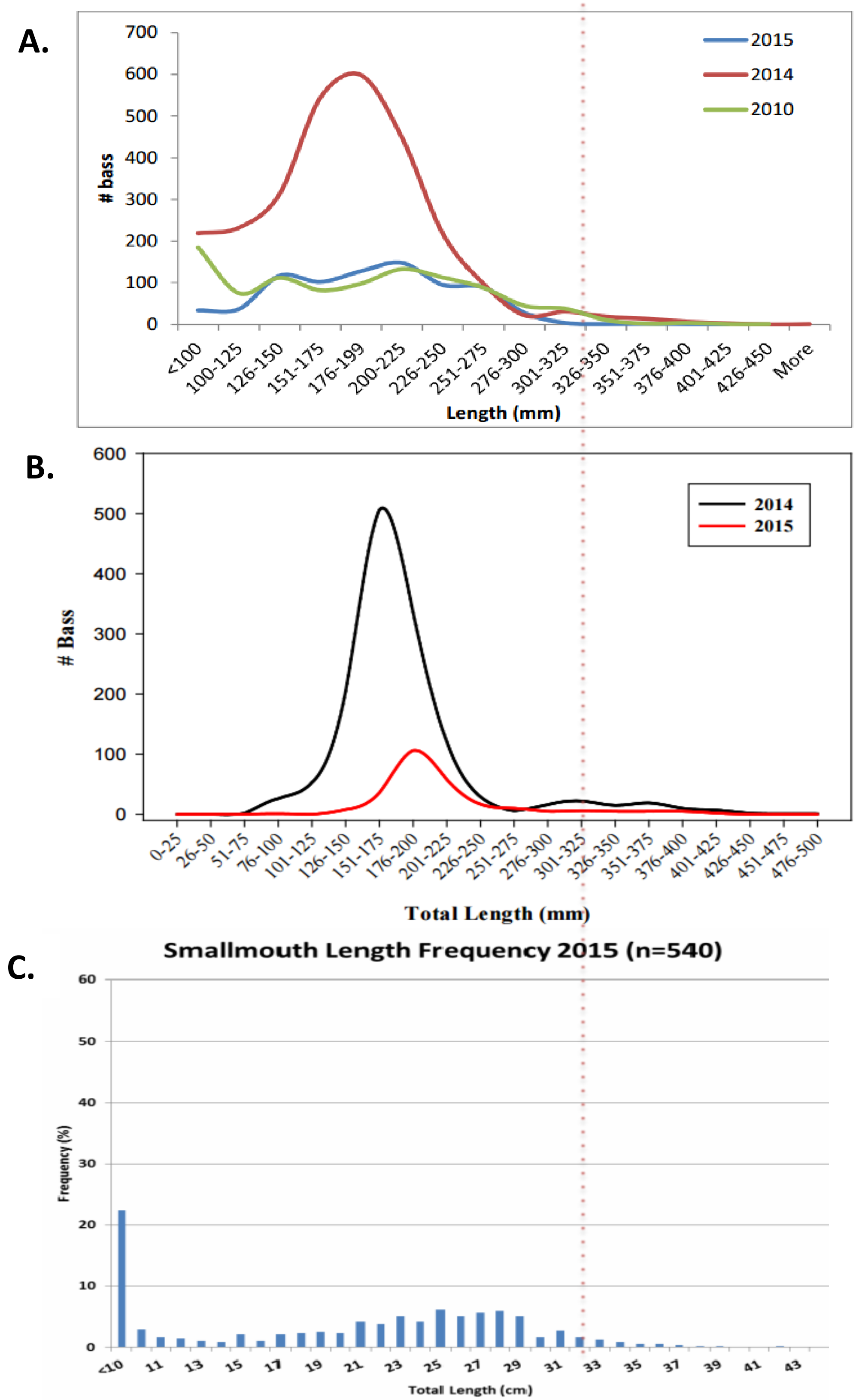

Figure 7. Size structure of smallmouth bass captured in portions of designated critical habitat for Colorado pikeminnow in the Green and Colorado Rivers. A: Echo Park to Split Mountain in 2010, 2014, and 2015 (Jones et al. 2015); B: Desolation and Gray Canyons 2014 and 2015 (Jones et al. 2015); C: Colorado River from Silt, CO to the Green River confluence (Francis and Ryden 2016). Dotted vertical line represents 325 mm, indicating a direct competitor to adult Colorado pikeminnow according to Martinez (2012). Note C has a differing Y axis (percent) than A&B (total abundance). In box A, similar size structure of 2010 and 2015 result from both years being 3 years after a low flow, high smallmouth bass production year

Scenario 3: Increased survival of young Colorado pikeminnow via reduced nonnative fish predation

The reduced numbers of large nonnative piscivorous fish is appropriate to consider for adjustments to carrying capacity within the model (Scenario 2 above). However, the abundant numbers of walleye and smallmouth bass below those size limits (Figure 7 above) still represent a large predatory threat to young pikeminnow, especially age-0 and age-1 individuals in nursery habitats. Smallmouth bass are able to prey upon young Colorado pikeminnow in their first summer of life, representing a pronounced predatory threat, especially in lower flow years. Researchers have also documented walleye predation on Colorado pikeminnow as large as 300 mm (Francis and Ryden 2014), indicating that the predatory threat from nonnative species occurs in multiple years of early development (Bestgen and Hill in draft 2016).

The importance of age-0 production of Colorado pikeminnow for the maintenance of subsequent adult populations was demonstrated previously in scenario 1. In order to truly realize gains in Colorado pikeminnow production within nursery habitats from altered flow regimes, managers must counter the considerable negative impact that large numbers of smallmouth bass and walleye have on age-0 and age-1 pikeminnow in those habitats. As mentioned in scenario 2, the implementation of nonnative fish control actions has only recently reached a condition that the Recovery Program believes is sufficient to alter nonnative fish population dynamics.

Conditions considered in the PVA represent a period of reference where annual hydrology was frequently dry (see scenario 1), which allowed smallmouth bass to flourish in many Green River habitats. For example, the annual hydrology of 2007, 2010, 2012, and 2013 were quite conducive to high smallmouth bass production. Conditions considered in the PVA also represent the colonization of walleye in nursery habitats, prior to specific walleye removal efforts (Bestgen and Hill 2016 in draft).

To truly model the future conditions for Colorado pikeminnow, a new set of parameters should be considered that represent the commitment by Recovery Program stakeholders to continue to implement the nonnative management actions that are known to be the most effective and efficient.

Nonnative removal efforts:

The current strategy for removal of smallmouth bass is guided by a decade of field work, population dynamics modeling, and resulting suppression strategies. In addition, the Recovery Program also specifically targets walleye for removal, which is an additional action. As a result, the Recovery Program believes that in the future, its management of smallmouth bass and walleye will be more effective than the last decade. Key components of this strategy include:

- The removal of smallmouth surge during the spawning period is a core component of the nonnative fish management strategy and includes enhanced effort in multiple locations during this critical time;
- The installation of escapement devices on upstream reservoirs, especially Elkhead Reservoir and Rifle Gap Reservoir, should reduce the immigration of individuals into the riverine population, making removal efforts more effective; and
- Harvest regulations now either allow anglers to catch unlimited amounts of smallmouth bass in the basin (Colorado), or expressly prohibit the return of this species to upper basin waters inhabited by endangered fish (Utah and Wyoming).
- Removal of walleye is now a consistent part of mechanical removal efforts. Walleye have not demonstrated reproduction with rivers yet.

Therefore, under future conditions, population control for walleye and smallmouth bass can be assumed to be more effective than what was implemented in the mid-2000s. Concurrently, survival of age-0 Colorado pikeminnow will be elevated as a result of increased control. In fact, this may be one reason that age-0 Colorado pikeminnow catches are quite high in 2015 and 2016. That is, these recent years are providing both flow and fish community conditions that provide niche space for adequate age-0 Colorado pikeminnow production.

PVA scenario

In order to model improved nonnative species management, an increase in the survival rates of Colorado pikeminnow from age-0 to sub-adult stages (~300 mm) by a factors of 5% up to 20% could be used.

In order to model improved nonnative species management, increases in the survival rates of Colorado pikeminnow from age-0 to sub-adult stages (~300 mm) by a factors of 5% up to 20% are justified. For example, PVA input parameters quantify survival of age-0 cohorts are 20.7% in the Green River Recovery Unit (Bestgen unpublished data). Modeling survival rates of 21.7%, 22.8%, 23.8%, and 24.8% could demonstrate management actions have a meaningful impact to Colorado pikeminnow. Modeling this increase for all cohorts simultaneously is most logical; that is, in a revised model, increases to all cohort survival rates should be equivalent for ages 1 to 5.

Moderate increases in survival, such as 5 and 10% are plausible under more effective mechanical removal that is currently being implemented. More aggressive increases in survival, such as 15 and 20%, are a potential outcome of basin-wide reductions in smallmouth bass, such as implementing a smallmouth bass spike flow (Bestgen and Hill 2016).

Table 4. Suggested incremental increases in survival rates to represent nonnative fish removal.

	Age-1	Age-2	Age-3	Age-4	Age-5
Existing survival rate in PVA model	0.207	0.309	0.411	0.514	0.616
5% increase	0.217	0.325	0.432	0.539	0.646
10% increase	0.228	0.340	0.452	0.565	0.677
15% increase	0.238	0.356	0.473	0.591	0.708
20% increase	0.248	0.371	0.494	0.616	0.739

Scenario 4: Increased adult survival via screening a problematic irrigation structure

In the Green River sub-basin Colorado pikeminnow spawn primarily in two discrete locations – lower Yampa Canyon and Gray Canyon. Resident adults from across the Green River sub-basin migrate to one of these two spawning locations each spring and then return their resident habitats in late summer or fall. This migratory life history results in adult Colorado pikeminnow interacting with a high proportion of the available habitat in the sub-basin, rather than simply encountering their resident habitat. Based on recent monitoring data, the Recovery Program believes that non-trivial numbers of adult Colorado pikeminnow are being entrained into the Green River Canal near Green River, Utah on their post-spawn migration back to their resident habitats, likely increasing the adult mortality rate of that portion of the population.

Immediately downstream of the Gray Canyon spawning location is the Green River Diversion, just upstream of Tusher Wash (north of Green River, Utah). The western portion of this diversion supports a large water supply channel, called the 'raceway', providing irrigation and hydropower flows. Based on the layout of the raceway, hydro facility, and Green River Canal, the current hypothesis is that adult fish are entrained into the terminal portion of the raceway, the Green River Canal, at a disproportionally high rate, because the entrainment rate into the canal is likely elevated by the amount of water conveyed by the raceway.

The raceway typically conveys around 780[2] cfs in its half mile long channel. Although 660 cfs is returned to the river through a hydro-electric generating station, that return flow (and 35 cfs irrigation intake) is screened with 1.75 inch aperture grates, which prevent large bodied fish from returning to the river[3]. Because the hydro facility is screened, any fish that that reaches the end of the raceway must either swim back upstream or enter the Green River Canal, where the remaining 85 cfs is entrained for agriculture purposes.

The canal operates with an unscreened headgate, allowing fish to still return to the river by swimming upstream. However, about a half mile below this headgate is an underground siphon that is much more difficult for fish to swim through in the upstream direction. In order to attempt to quantify the entrainment problem at the canal, the Recovery Program installed a passive monitoring system in the Green River Canal. In 2013 the system consisted of antennas between the headgate and the siphon, and in 2014 antennas below the siphon were added. Data provided via the antennas have been invaluable in understanding entrainment.

Initial data analysis indicate that fish of all species entering the canal, but not passing through the siphon, are able to return to the river; whereas fish that bypass the siphon are much less likely to return to the river (Stahli et al. 2017). Therefore, the Recovery Program considers fish that pass the siphon as the true measure of entrainment[4]. Colorado pikeminnow individuals are primarily entrained after the spawning period, typically in July and August. This is logical, as these individuals are swimming in the downstream orientation, using shoreline habitats, which increases the exposure to the raceway.

From 2014 to 2016, 13, 6, and 9 Colorado pikeminnow were detected at the siphon antennas, respectively (Table 5). Fortunately, 5 of those fish have been detected subsequently in the river, indicating that Colorado pikeminnow can escape entrainment into the canal. Therefore, the assumed annual total mortality of Colorado pikeminnow in the Green River Canal has been less than ten individuals over the past three years (Table 5).

Unfortunately, 2013 data only describe the number of fish upstream of the siphon, which the Recovery Program no longer considers entrainment. Nevertheless, the year 2013 is important because the annual hydrology was much lower than the three subsequent years, and entrainment rates were commensurately higher. For example, in 2013 85 Colorado pikeminnow were detected at the antennas upstream of the siphon, whereas in 54 were detected at those antennas in all three years of 2014-2016 combined (Table 5).

Using proportional relationships derived from 2014 to 2016, approximately 50% of Colorado pikeminnow detected at the upstream antennas eventually become entrained downstream of the siphon ([13+6+9] / [19+18+15] = 54%). Applying that proportion to the 85 fish indicates that approximately 43 fish were expected to be downstream of the siphon. Using the same process, approximately 18% likely escaped the canal and returned to the river ([4+0+1] / [13+6+9] = 18%).

[2] An estimate of 85 cfs is used for the unscreened Green River Canal, the remainder is screened, with 35 cfs going to irrigation demand and 660 cfs returned to river via hydropower turbines.
[3] Based on body size estimates, Colorado pikeminnow 280 mm and greater are excluded by the grate size.
[4] Therefore data collected in 2013 does not directly measure entrainment into the canal, because that data is only upstream of the siphon.

Applying both of these estimates indicates an assumed mortality rate of 35 individuals in the dry year of 2013 (Table 5).

Table 5. Entrainment data collected at the Green River Canal using passive monitoring (antennas). Note data denoted with * are derived using proportions from the subsequent years. Data provided by Stahli et al. (2017).

Year	Individuals detected upstream of siphon	Individuals detected downstream of siphon	Individuals later detected in river	Assumed Mortalities
2013	85	43*	8*	35*
2014	19	13	4	9
2015	18	6	0	6
2016	15	9	1	8

PVA scenario

Modeling an increase in adult survival (otherwise stated as a reduction in adult mortality) for the Green River sub-basin population could evaluate how reducing the entrainment in this irrigation canal would benefit the species. Because the adults that interact with the Green River canal are primarily from the Lower Green River and Desolation-Gray Canyon portions of the population, it is likely that the increase in survival will impact those fish the most.

Modeling an increase of 1% in the overall Green River sub-basin adult survival rate will represent the reduced mortality resulting from screening the Green River Canal.

In the dry year 2013, an estimate of 35 fish are assumed to perish in the Green River Canal represents nearly 5% of that years abundance estimate for the two nearby river reaches (Table 6). For the entire Green River sub-basin, the 35 individuals entrained in 2013 represent 1.6% of the population. Increases in survival in wetter years, such as 2014 through 2016 are substantially less than those predicted from 2013, although with a population of just over 2000, losing even ten adults a year could be important.

The adult survival of adult Colorado pikeminnow in the Green River sub-basin could be increased by 1% to represent the prevention of entrainment into the Green River Canal. One percent is likely a conservative estimate that covers both wetter years and drier years.

Table 6. Key population parameters for the Lower Green River and Desolation-Gray Canyon reaches of the Green River sub-basin Colorado pikeminnow population. Data from Bestgen and Hill, 2016 in draft.

	Lower Green River reach	Desolation-Gray Canyon reach	Desolation-Gray & Lower Green River reaches	Entire Green River Recovery Unit
2013 population estimate	244	489	733	2128
2000 to 2013 survival rate	0.78	0.7		

Entrainment prevention will also benefit large numbers of juvenile and sub-adult Colorado pikeminnow, but the data do exist to model these changes. Younger fish do likely migrate less, resulting in potentially lower exposure to this facility. However, it is worth mentioning that the lower Green River reach is the primary emigration reach for the species, with young fish reared in the nursery habitats of the lower Green River eventually emigrating to upstream habitats as sub-adults and adults (Bestgen and Hill 2016 in draft, Table 16). Also, young Colorado pikeminnow have been transferred from this canal during post-irrigation season salvage efforts.

Justification

The entrainment of endangered fish into the western raceway and Green River Canal has been considered a problem by Recovery Program stakeholders for many years, but technically feasible and cost effective solutions have been hard to find. Recovery Program stakeholders assumed that this location was a source of additional mortality for adult Colorado pikeminnow migrating within the system, but did not have verification until antenna systems were installed. The large number of entrained fish in 2013 put the Recovery Program into action to screen this canal.

With the completion of the rehabilitation of the Green River Diversion, the Recovery Program is now in the final stages of negotiating installation of a weir wall and fish screen at the Green River Canal. The structure has been partially designed and planned, and the Recovery Program has committed to funding this project. Installation of this facility and reduction in entrainment is expected to be completed in the next 2-3 years.

Summary of PVA Scenarios:

By considering achievable management actions and the corresponding population responses of those actions, the impact of specific management actions can be modeled using the PVA. Four management actions were chosen determine how Colorado pikeminnow populations may respond to Recovery Program implementation of planned or ongoing actions. An added benefit of this exercise is to demonstrate how a management action can improve the condition of the species. Because the viability of the species is the fundamental objective of the Recovery Program, these types of analyses assist all stakeholders in valuing the actions in a more tangible way.

By modeling ongoing and planned actions, the PVA outputs represent a more accurate prediction of the future species viability. That is, rather than modeling a future in which the species condition repeats what conditions occurred in the past, the PVA would model the positive conservation actions to which the Recovery Program stakeholders are committed. Models proposed are:

- increased production of age-0 by via implementing modified base flow regimes;
- increased carrying capacity via removal of large bodied nonnative piscivorous taxa;
- increased juvenile and sub-adult survival rates via aggressive nonnative fish management actions; and
- increased adult survival via reduced entrainment into a problematic irrigation structure on a spawning migration route.

All four of these actions are independently justifiable to model, as the actions are planned or ongoing, and the resulting demographic rates are logically affected by the action. But even more importantly, all four actions can happen independently, meaning the PVA can model any and all combinations of the actions. That is, nonnative fish management, improved base flow regimes, and entrainment prevention at the Green River Canal can also all happen simultaneously. Therefore, the PVA can also model combinations of the actions to truly understand the future condition of the species under an aggressive, multifaceted Recovery Program. Once all of these single, and combined, scenarios are modeled, the PVA can provide a better understanding of how the Recovery Program will improve the condition of the Colorado pikeminnow, and what more needs to be done to ensure the short- and long-term viability of this important native fish.

Appendix A: Colorado pikeminnow production in the middle and lower Green Rivers, with corresponding flow.

year	Middle Green River Flow	Estimated # age-0 CPM in Middle Green	Lower Green River Flow	Estimated # age-0 CPM in LowerGreen
1979	1936	150987	3005	113171
1980	1939	95468	2691	313422
1981	2124	98123	2443	37693
1982	2931	112158	4109	30167
1983	5328	3076	7725	7438
1984	4091	5545	6608	2650
1985	2241	16372	3666	40926
1986	2307	71119	3817	191560
1987	1937	41507	2850	129873
1988	1270	143220	1906	410059
1989	1355	9106	1666	170317
1990	1139	43380	1259	29575
1991	1822	63973	2617	27540
1992	1531	24022	1812	14160
1993	1690	47869	2192	157497
1994	1593	1708	1699	35443
1995	1922	12287	3304	9960
1996	2023	12563	2459	60789
1997	3129	4546	5121	6058
1998	3047	9200	4683	35509
1999	2439	1909	4173	41680
2000	1393	12625	1739	54418
2001	1061	1492	1263	1344
2002	883	0	1113	1630
2003	1063	262	1246	11757
2004	1294	7938	1447	17818
2005	1813	3426	2579	10609
2006	1174	351	1703	29496
2007	1124	388	1435	96624
2008	2120	1602	2701	13700
2009	2479	37145	2785	76046
2010	2165	36609	2543	20337
2011	3686	0	5686	4214
2012	1403	121	1342	23980
2013	1506	8493	1625	5788
2014	2978	8679	3463	1336
2015	2118	28517	2328	101068
Mean	2,055.51	30,156.42	2,832.51	63,125.67
Standard	918.24	40,715.79	1,532.60	87,623.26

Dev				
Data to support Bestgen and Hill flow recommendations. Note red text with strikethrough was not used to compute mean and standard deviation because conditions did not match Bestgen and Hill recommendations.				
year	Middle Green River Flow	Estimated # age-0 CPM in Middle Green	Lower Green River Flow	Estimated # age-0 CPM in LowerGreen
1979	1936	150987	3005	113171
1980	1939	95468	2691	313422
1981	2124	98123	2443	37693
1982	2931	112158	~~4109~~	~~30167~~
1983	~~5328~~	~~3076~~	~~7725~~	~~7438~~
1984	~~4091~~	~~5545~~	~~6608~~	~~2650~~
1985	2241	16372	3666	40926
1986	2307	71119	~~3817~~	~~191560~~
1987	1937	41507	2850	129873
~~1988~~	~~1270~~	~~143220~~	1906	410059
~~1989~~	~~1355~~	~~9106~~	~~1666~~	~~170317~~
~~1990~~	~~1139~~	~~43380~~	~~1259~~	~~29575~~
1991	1822	63973	2617	27540
~~1992~~	~~1531~~	~~24022~~	1812	14160
~~1993~~	~~1690~~	~~47869~~	2192	157497
~~1994~~	~~1593~~	~~1708~~	~~1699~~	~~35443~~
1995	1922	12287	3304	9960
1996	2023	12563	2459	60789
~~1997~~	~~3129~~	~~4546~~	~~5121~~	~~6058~~
~~1998~~	~~3047~~	~~9200~~	~~4683~~	~~35509~~
1999	2439	1909	~~4173~~	~~41680~~
~~2000~~	~~1393~~	~~12625~~	1739	54418
~~2001~~	~~1061~~	~~1492~~	~~1263~~	~~1344~~
~~2002~~	~~883~~	~~0~~	~~1113~~	~~1630~~
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2008	2120	1602	2701	13700
2009	2479	37145	2785	76046
2010	2165	36609	2543	20337
2011	~~3686~~	~~0~~	~~5686~~	~~4214~~
~~2012~~	~~1403~~	~~121~~	~~1342~~	~~23980~~
~~2013~~	~~1506~~	~~8493~~	~~1625~~	~~5788~~
2014	2978	8679	3463	1336
2015	2118	28517	2328	101068
mean	2,193.76	46,614.47	3,031.35	71,757.42
std dev	335.67	43,559.13	586.51	78,244.43

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

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IUCN SSC Conservation Planning Specialist Group

In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

5. McAbee, K. 2017b. Scenario 4: Increased adult survival via screening a problematic irrigation structure. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Scenario 4: Increased adult survival via screening a problematic irrigation structure

In the Green River sub-basin Colorado pikeminnow spawn primarily in two discrete locations – lower Yampa Canyon and Gray Canyon. Resident adults from across the Green River sub-basin migrate to one of these two spawning locations each spring and then return to their home range habitats in late summer or autumn. This migratory life history results in adult Colorado pikeminnow interacting with a high proportion of the available habitat in the sub-basin, rather than simply encountering their resident habitat. Based on recent monitoring data, the Recovery Program believes that non-trivial numbers of Colorado pikeminnow are being entrained into the Green River Canal near Green River, Utah. Adults are likely entrained on their post-spawn migration back to their resident habitats; juveniles and recruit sized fish are likely entrained on their transition from nursery habitats in the lower Green River to upstream home ranges. These entrainment rates are likely increasing mortality rates of adult, recruit, and juvenile Colorado pikeminnow.

Immediately downstream of the Gray Canyon spawning location is the Green River Diversion, just upstream of Tusher Wash (north of Green River, Utah). The western portion of this diversion supports a large water supply channel, called the 'raceway', providing irrigation and hydropower flows. Based on the layout of the raceway, hydro facility, and Green River Canal, the current hypothesis is that adult fish are entrained into the terminal portion of the raceway, the Green River Canal, at a disproportionally high rate, because the entrainment rate into the canal is likely elevated by the amount of water conveyed by the raceway.

The raceway typically conveys around 780[1] cfs in its half mile long channel. Although 660 cfs is returned to the river through a hydro-electric generating station, that return flow (and 35 cfs irrigation intake) is screened with 1.75 inch aperture grates, which prevent moderate and large-bodied fish from entering the hydro facility and also prevent them returning to the river[2]. Thus, any fish that reaches the end of the raceway must either swim back upstream or enter the Green River Canal, where the remaining 85 cfs is entrained for agriculture purposes.

The canal operates with an unscreened headgate, allowing fish to still return to the river by swimming upstream. However, about a half mile below this headgate is an underground siphon that is much more difficult for fish to swim through in the upstream direction. In order to attempt to quantify the entrainment problem at the canal, the Recovery Program installed a passive monitoring system in the Green River Canal. In 2013 the system consisted of antennas between the headgate and the siphon, and in 2014 antennas downstream of the siphon were added. Data provided via the antennas aid understanding entrainment.

Initial data analysis indicates that fish of all species entering the canal, but not passing through the siphon, are able to return to the river; fish that bypass the siphon are much less likely to return to the river (Stahli et al. 2017). Therefore, the Recovery Program considers fish that pass the siphon as the true measure of entrainment[3]. Colorado pikeminnow individuals are primarily entrained after the spawning period, typically in July and August. This is logical, as these individuals are swimming in the downstream orientation, using shoreline habitats, which increases the exposure to the raceway.

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[1] An estimate of 85 cfs is used for the unscreened Green River Canal, the remainder is screened, with 35 cfs going to irrigation demand and 660 cfs returned to river via hydropower turbines.

[2] Based on body size estimates, Colorado pikeminnow 280 mm and greater are excluded by the grate size.

[3] Data collected in 2013 does not directly measure canal entrainment, because that data is only upstream of the siphon.

From 2014 to 2016, 16, 8, and 14 Colorado pikeminnow were detected at the siphon antennas, respectively (Table 5). Of those, 13 have been detected subsequently in the river, indicating that Colorado pikeminnow can escape after entrainment into the canal. Therefore, the assumed annual total mortality of Colorado pikeminnow in the Green River Canal has been approximately ten individuals (25 total) from 2014-2016 (Table 5).

Unfortunately, 2013 data only describe the number of fish upstream of the siphon, which the Recovery Program no longer considers entrainment. Nevertheless, the year 2013 is important because the annual hydrology was much drier than the three subsequent years because a higher proportion of water is diverted from the river, and entrainment rates of pikeminnow were commensurately higher. For example, in 2013 102 Colorado pikeminnow were detected at the antennas upstream of the siphon, whereas only 55 were detected at all antennas from 2014-2016 combined (Table 5).

Using proportional relationships derived from 2014 to 2016, approximately 69% of Colorado pikeminnow detected in the canal eventually become entrained downstream of the siphon ([16+8+14] / [21+18+16] = 69%). Applying that proportion to the 102 fish indicates that approximately 70 fish were expected to be downstream of the siphon. Using the same process, approximately 34% likely escaped the canal and returned to the river ([7+2+4] / [16+8+14] = 34%). Applying both of these estimates indicates an assumed mortality rate of 46 individuals in the dry year of 2013 (Table 5).

Table 5. Entrainment data collected at the Green River Canal using passive monitoring (antennas). Data denoted with ***** are estimated numbers downstream of the siphon or later detected in the river and are derived using proportions from 2014-2016. Data provided by Stahli et al. (2017).

Year	Total individual Colorado pikeminnow detected in the canal	Individuals detected downstream of siphon	Individuals later detected in river	Assumed Mortalities of tagged fish
2013	102	70*	24*	46*
2014	21	16	7	9
2015	18	8	2	6
2016	16	14	4	10

However, those 46 individuals only represent the mortality of fish detectable by the antennas; there is also a substantial portion of the adult Colorado pikeminnow population that does not have PIT tags and are not detectable by the antennas. Using data from the last population estimation period (2011 to 2013), we calculated that 44% of adult Colorado pikeminnow (those > 450 mm TL) did not have tags upon first encounter. Accounting for untagged fish that could not be detected, we estimate that 4.14% of the adult Green River subbasin population died in the Green River Canal in 2013 and a mean of 0.744% of the adult population died between 2014 and 2016 (Table 6). These reductions are much higher when only looking at the adjacent populations in the Desolation-Gray Canyon (upstream) and lower Green River reaches (downstream).

Increased mortality in 2013 was the result of increased entrainment of water into the canal; that is, in 2013 the Green River Canal took approximately 35% of the river's flows, compared to approximately 20% between 2014 and 2016. In very dry years such as 2002, the canal can divert nearly all the river flow. This demonstrates that summer flow in the Green River is an important factor to consider. If we consider that 30% of years are expected to be similar to 2013 (moderately dry and dry classifications from Muth et al. 2000), and the remaining 70% of years are likely similar to 2014, 2015, and 2016, we can create a weighted annual mortality rate that is the approximate annual mortality rate under all hydrologic conditions.

0.3 * 4.14% + 0.7 * 0.744% = 1.76% weighted annual mortality rate

Table 6. Estimated adult mortality rates of Colorado pikeminnow resulting from entrainment into the Green River Canal 2013-2016.

Year	Assumed Mortalities of tagged fish	Total expected mortalities of tagged and untagged fish	Reduction to Green River subbasin population	Reduction to Lower Green and Deso-Gray units
2013	46*	83	4.1%	9.7%
2014	9	16	0.8%	1.9%
2015	6	11	0.5%	1.3%
2016	10	18	0.9%	2.1%

Adult sized fish are not the only size class exposed to entrainment mortality. In fact, smaller sized fish are more likely to perish once in the canal because of reduced swimming speed and increased predation risk in such habitats. Recovery Program crews have collected eight Colorado pikeminnow less than 200 mm during autumn canal salvage in the last two years, demonstrating entrainment of small pikeminnow is a concern. Unfortunately, approximately 95% of juvenile (less than 400 mm) and 90% of recruit (400 to 449 mm) sized Colorado pikeminnow do not have PIT tags, rendering antenna monitoring ineffective at documenting entrainment of these size classes. Thus, no Colorado pikeminnow juveniles or recruits were detected at the siphon antenna.

> Modeling a 1.76% increase in survival rate of adult and recruit sized Colorado pikeminnow in the Green River sub-basin, and a 3.52% increase in survival of smaller size classes, will represent the reduced mortality resulting from screening the Green River Canal.

Although we have no estimates for juvenile and recruit entrainment mortality from antenna data, we know this is an important consideration for the sub-basin's population demographics. We also know these mostly untagged fish are expected to have higher mortality rates from entrainment than adults. Thus, we doubled the mortality rate of adults and considered fish less between 50 and 399 mm to have a 3.52% weighted mortality rate. While this estimate is not derived from empirical data, the estimate is reasonable and conservative.

Many sources of uncertainty may affect this estimate. On one hand, young fish survival may be higher than we estimated because they may not be entrained at rates comparable to adults, or if entrained, they can return to the river through the hydropower facility grates and adults cannot. Alternatively, young fish survival may be higher than adults because the rebuilt Green River Diversion (2016) may make the Green River Canal more efficient and increase risk of small fish to facilities such as irrigation pumps and sluicing structures. Furthermore, mortality differences may exist over the size range of fish between age-1 and age-6 fish, with higher rates among the smaller and younger fish. While these uncertainties are worth considering, we believe the potential positive and negative effects balance each other out and that doubling the adult mortality rate for juvenile fish was most appropriate.

PVA scenario

Modeling an increase in adult survival (otherwise stated as a reduction in adult mortality) for the Green River sub-basin population would show how reducing the entrainment in this irrigation canal would benefit the species. Because the juveniles and recruits that interact with the Green River canal are primarily from the Lower Green River and Desolation-Gray Canyon portions of the population, it is likely that the increase in survival will impact those fish the most. Adults from these two units are similarly more likely to be exposed to entrainment, but adults from throughout the population have been documented in the canal.

In the dry year 2013, the estimated 83 fish assumed to perish in the Green River Canal represents 4.14% of the mean adult abundance estimate from 2011-2013 for the entire sub-basin, which was 1999 adult fish. Increased survival in wetter years, such as 2014-2016, indicate substantially lower mortality than predicted from 2013, although any mortality with a declining population may be important.

To implement the PVA scenario, survival of adult and recruit Colorado pikeminnow in the Green River sub-basin could be increased by 1.76% to represent the prevention of entrainment into the Green River Canal using the weighted average of mortality from above. Furthermore, the survival of juvenile fish (< 400 mm TL) could be increased by 3.52% to represent the reality that many smaller sized fish are also currently being entrained into the facility.

Justification

The entrainment of endangered fish into the western raceway and Green River Canal has been considered a problem by Recovery Program stakeholders for many years, but technically feasible and cost effective solutions have been hard to find. Recovery Program stakeholders assumed that this location was a source of additional mortality for adult Colorado pikeminnow migrating within the system, but did not have verification until antenna systems were installed. The large number of entrained fish in 2013 put the Recovery Program into action to screen this canal.

With the completion of the rehabilitation of the Green River Diversion, the Recovery Program is now in the final stages of negotiating installation of a weir wall and fish screen at the Green River Canal. The structure has been partially designed and planned, and the Recovery Program has committed to funding this project. Installation of this facility and reduction in entrainment is expected to be completed in the next 1-2 years.

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

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Senior Program Officer
IUCN SSC Conservation Planning Specialist Group

In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

6. Valdez, R.A., T. Francis, D. Elverud, and D. Ryden. 2017. Colorado Pikeminnow PVA Scenarios for the Upper Colorado River Subbasin. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Colorado Pikeminnow PVA Scenarios for the Upper Colorado River Subbasin

Rich Valdez, Travis Francis, Darek Elverud, and Dale Ryden

April 10, 2017

The following are four scenarios that we developed for consideration of PVA analysis for the Colorado Pikeminnow in the Upper Colorado River Subbasin:

1. Flow to Age-0 Relationship

Kevin McAbee's summer base flow scenario. We believe this is a worthwhile scenario to be included in the PVA, but have doubts about the feasibility of augmenting summer base flows in the Colorado River. Summer base flows met the revised flow recommendations during every year of the analysis except 2002. An extremely dry year such as 2002 would be the most difficult case in which to increase summer base flow. In every other year in the scenario presented by Kevin McAbee, summer base flows already met or exceeded the revised flow recommendations.

Colorado River summer base flow scenario for PVA consideration

The concepts supporting the revised flow recommendations for Colorado pikeminnow age-0 production in the Green River are also applicable in the Colorado River. Using the same general process as Bestgen and Hill, and using long term monitoring of age-0 pikeminnow production in the Colorado River (1986-2014), we can analyze age-0 production as a function of flow at the Colorado River near the Colorado Utah state line (gage #09163500).

Long term annual monitoring of age-0 pikeminnow in the Colorado River began in 1986 and continues today. The trend in the age-0 density shows a marked decline, similar to that in the Green River (Figure 1). Between 1997 and 2014, only a few years produced more than nominal age-0 pikeminnow. However, reductions in mean August and September base flows in the lower Colorado River (Figure 2) do not show as substantial a decline as the age-0 pikeminnow density, nor are the declines in mean base flow in the Colorado as severe as the declines in flow in the Green River. Although, the minimum and maximum mean base flow are both reduced from 2000 to 2014 when compared to the pre-2000 period.

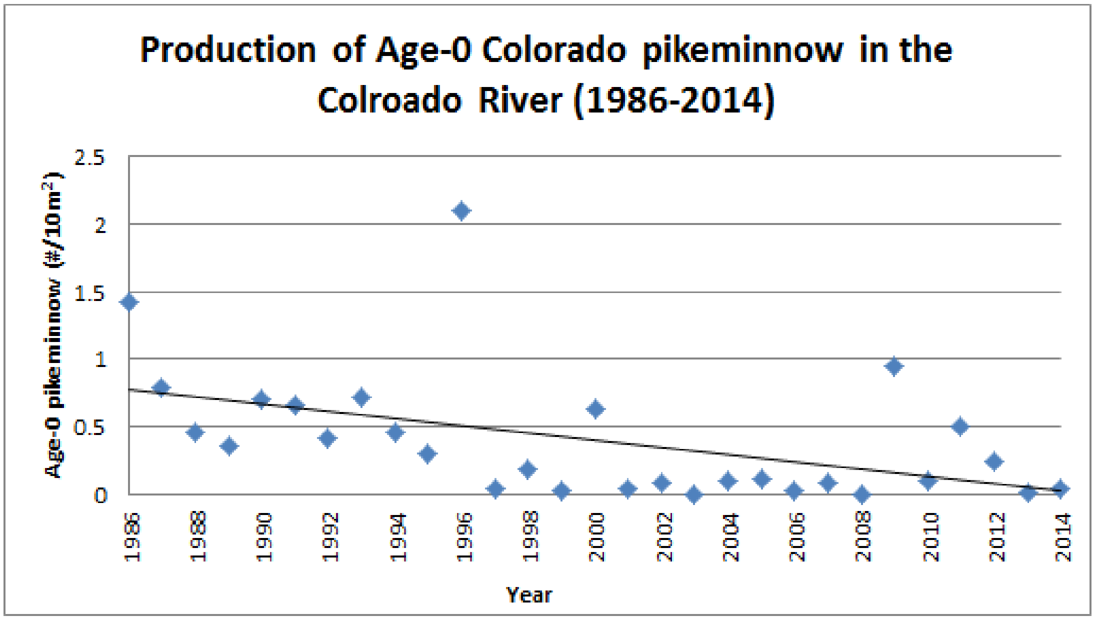

Figure 1. Annual age-0 Colorado pikeminnow density in the Colorado River since 1986.

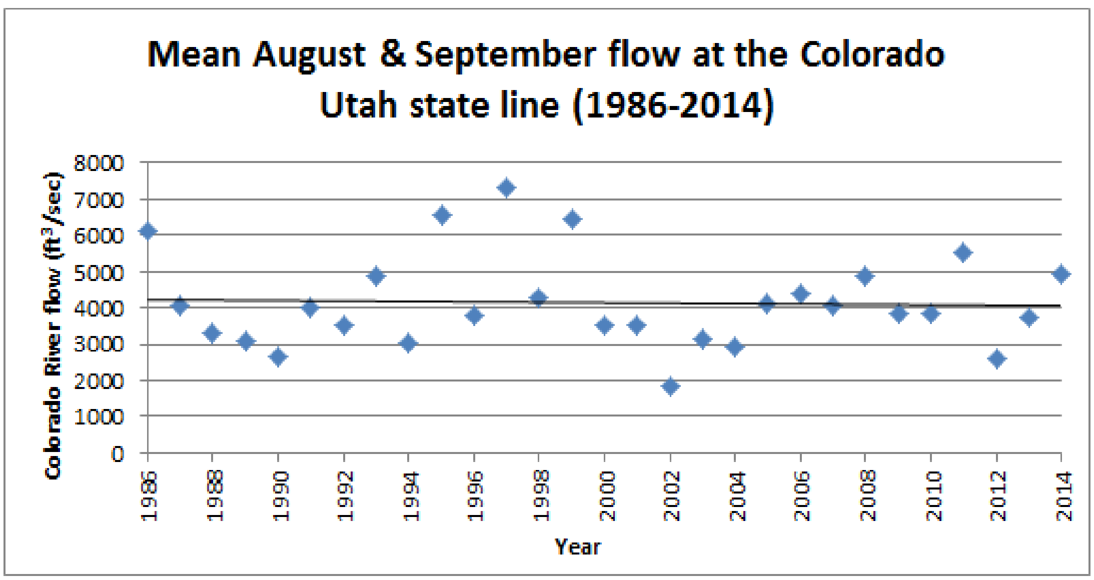

Figure 2. Mean August & September base flow measured at the Utah Colorado state line gage.

Analyzing age-0 pikeminnow production as a function of mean August to September flows (Figure 3) demonstrates a similar, albeit more variable, pattern as that shown in Bestgen and Hill's Figure 18. That is, moderate flows show an increase in age-0 production, with extremely higher and lower flows demonstrating lower production.

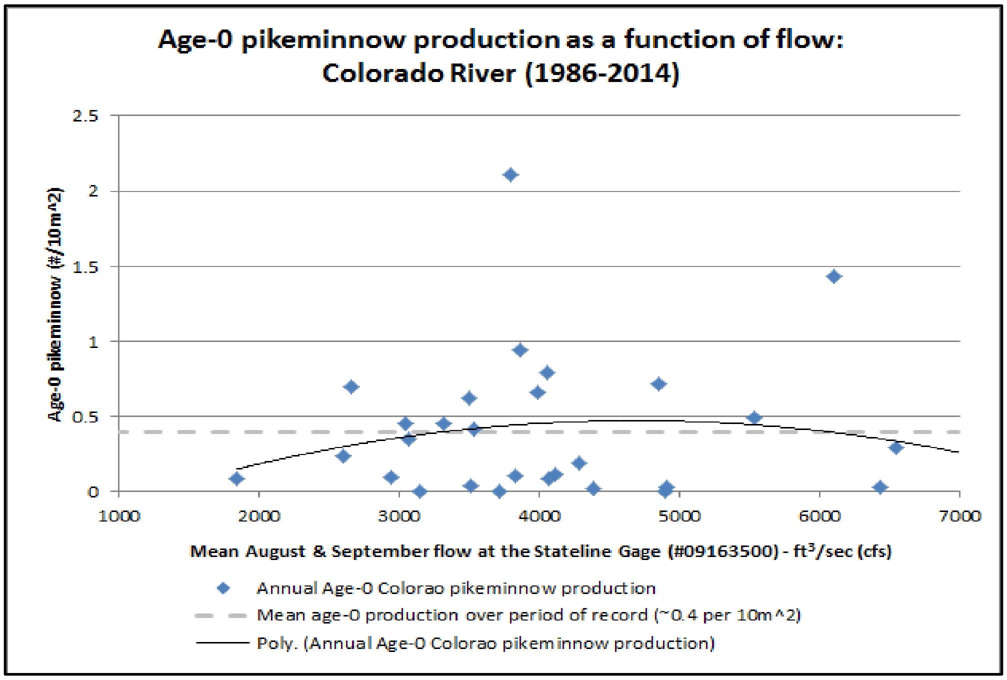

Figure 3. Age-0 Colorado pikeminnow density as a function of mean August and September flow. Note the parabolic relationship similar to Bestgen and Hill's Figure 18 is present, but less pronounced. Grey dashed line is mean annual production over the period of record

Table 1. Flow recommendations and ecological goals of the Colorado River as measured at the Utah Colorado state line gage as described in McAda et al.

	Exceedance	Lower base flow recommendation	Upper base flow recommendation	Ecological goal
Dry	90-100%	1800	2500	Backwater habitats are available, but not maximized; high Colorado pikeminnow growth rate
Moderately Dry & Below Average	50-90%	2500	4000	Backwater quantity and area are maximized; constant habitat and warm water allow for elevated growth and production of Colorado pikeminnow
Above Average & Moderately Wet	10-50%	3000	4800	
Wet	10%	3000	6000	Backwaters available but fewer and smaller

Current flow recommendations for the Colorado River (Table 3; McAda et al.) call for summer base flows in the range of 1800-6000 cfs, based on annual hydrologic conditions. This range incorporates the bulk of the flow conditions since 1986 (shown as vertical black dashed lines in Figure 4). The goals of these recommendations are to provide backwaters in all years, and to maximize the availability in moderate years. By analyzing the mean age-0 pikeminnow production across these flow recommendations, we can indirectly determine their ability to meet the ecological goals of each category (Table 4).

Since 1986, flows have occurred in the dry year classification (1800 to 2500) and the lower portion of the moderately dry classification (2500 to 3000 cfs) four times (Figure 4). However, only once out of those four times was the annual age-0 production above average, with the other three times close to zero. Conversely, the highest flow recommendation in the wet years, seems to be appropriate, with only one year out of three producing above average age-0 pikeminnow when flows exceed 6000 cfs.

Table 2. Mean age-0 production of Colorado pikeminnow under McAda et al. flow recommendations

	Lower base flow recommendation	Upper base flow recommendation	mean age-0 CPM produced per 10m^2
Dry	1800	2500	0.0820
Moderately Dry & Below Average	2500	4000	0.4796
Above Average & Moderately Wet	3000	4800	0.4103
Wet	3000	6000	0.3209

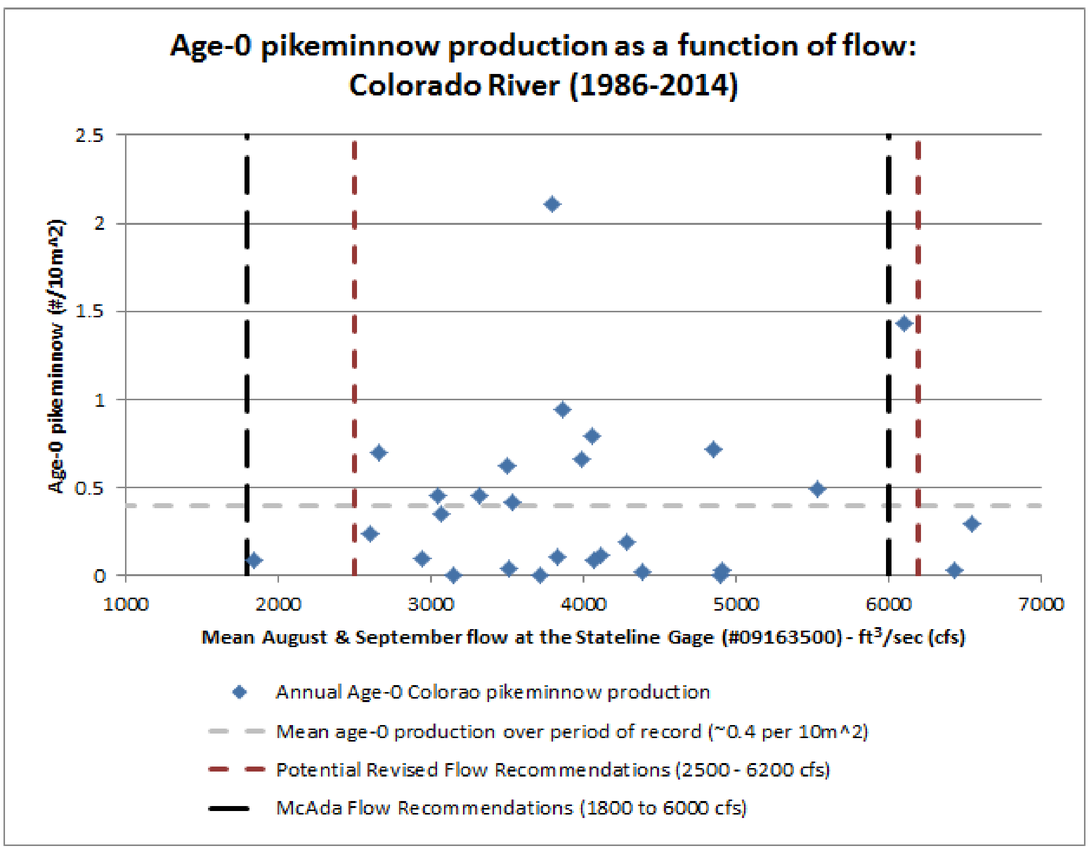

Figure 4. Age-0 Colorado pikeminnow density under current (vertical black dashed lines) and potentially revised (vertical red dashed lines) flow recommendations.

If we follow the pattern that Bestgen and Hill undertook when revising the Muth et al. (2000) flow recommendations, we can approximate similar revised flow recommendations for the Colorado River. Bestgen and Hill increased the minimum flow recommendation in dry years to a flow level that yielded meaningful production (from 900 cfs to 1700 cfs in the middle Green River and from 1300 to 1700 in the lower Green River). In the Colorado River, if dry year minimum flow recommendations were increased from 1800 to 2500 cfs, mean production would increase substantially for that hydrologic year type (Table 5; Figure 4). Bestgen and Hill also recommended selecting a wet year maximum flow level that precluded low pikeminnow production by limiting overtopping of backwaters and cold water growing conditions. In the Colorado River, if we simply increased McAda's et al. wet year maximum by 200 cfs, we include an additional high production year.

To quantify that potential increase, we can compare the mean annual production under each hydrologic classification using the current and revised flow recommendations (Table 5). By increasing the dry year classification up to 2500 cfs, we eliminate the poorest production year on record, and the only year to meet the current dry year flow recommendations. Increasing the dry year minimum to 2500 increases age-0 density by over 300%, which seemingly meets the ecological goal found in McAda et al. That is, by raising the minimum flow recommendation to 2500 cfs, we still see some pikeminnow production, albeit reduced; whereas from 1800 to 2500 cfs almost now pikeminnow production took place (Table 5).

Table 3. Comparison of age-0 production under current and revised flow regimes.

Hydrologic classification	McAda et al. recommendations		mean CPM produced per 10m^2	Revised flow recommendations to increase age-0 production		mean CPM produced per 10m^2	Increase in production (% increase)
Dry	1800	2500	0.0820	2500	3000	0.346	0.264 (322%)
Moderately Dry & Below Average	2500	4000	0.4796	3000	4000	0.513	0.033 (7%)
Above Average & Moderately Wet	3000	4800	0.4103	3500	4800	0.469	0.059 (14%)
Wet	3000	6000	0.3209	3500	6200	0.487	0.166 (52%)

By shifting the lower minimum flow recommendation up and commensurately raising other hydrologic year flow recommendations, we can increase the age-0 pikeminnow production in each year category (Table 5). While these flow recommendations are purely hypothetical (having not received peer review) and would potentially be difficult to implement (they would have to be vetted substantially), they offer a test case for PVA implementation.

Across this hypothetical revision of the flow recommendations, we ended the age-0 production data in 2014 because the successful production in 2015 actually skewed results for revised flow recommendations much higher than they would have been otherwise. We considered 2015 a data point for testing the revised recommendations.

In 2015, mean flows at the Utah Colorado state line gage were 3994 cfs which match the upper limit of the "below average" classification in both the current and revised recommendations. In 2015, age-0 density was 10.6 fish per square meter, which is 27 times the mean production from 1986 to 2014, and 5 times the previous highest density (Figure 6). Even more interesting is the fact that both of the two highest production years were very close in flow magnitude – 3994 cfs in 2015 and 3800 cfs in 1996. In fact, 4 of the 5 highest production years had flows between 3800 and 4100 cfs (years 2015, 1996, 2009, and 1987).

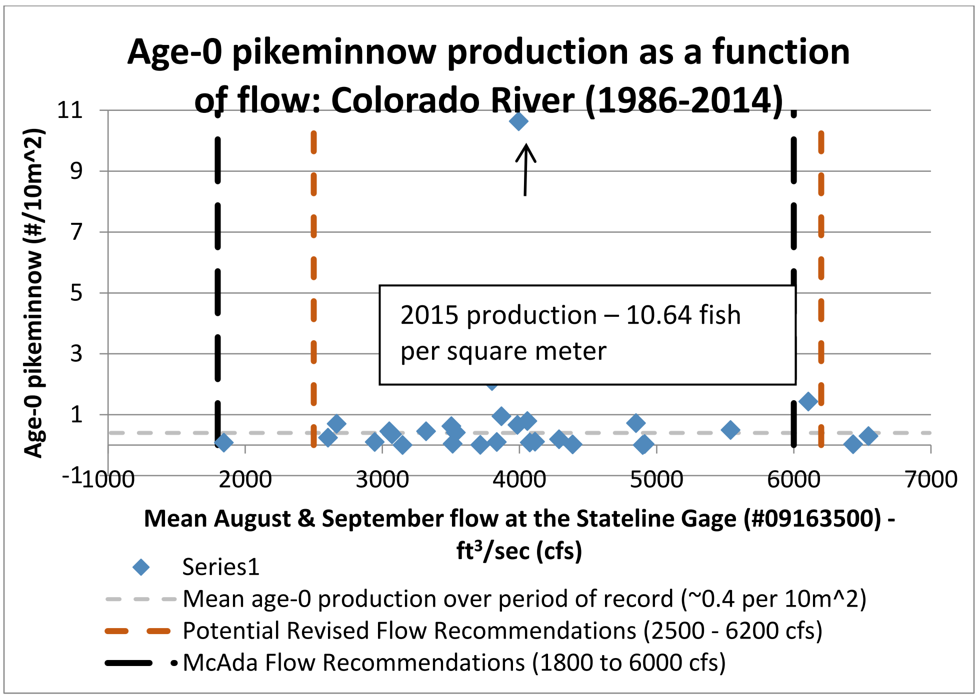

Figure 5. Inclusion of 2015 production in the comparison of age-0 Colorado pikeminnow density under current (vertical black dashed lines) and potentially revised (vertical red dashed lines) flow recommendations.

To provide a revised input table for PVA, we calculated total age-0 production from the densities presented above. Table 6 demonstrates the differing means and standard deviations for three data sets.

Table 4. Revised input parameters for PVA analysis (see Appendix A).

	1986 to 2014	Years meeting McAda Flow recommendations (>1800 cfs & <6000cfs)	Years meeting revised flow recommendation (>2500 & <6200 cfs)
Mean	28406	26866	30572
Standard deviation	33694	32023	34830

2. Predation

Increase adult carrying capacity and/or increase survival of juvenile CPM. Walleye presence in the Colorado River (Westwater Canyon to confluence) and smallmouth bass abundance (upstream of Westwater Canyon) are both potential scenarios that may need to be modeled differently due to the distribution of pikeminnow within the Colorado. That is, walleye overlap with all life stages of pikeminnow while our main area of smallmouth occupation overlaps habitat occupied by adult pikeminnow. As this is an ongoing management action, we believe it would be a worthwhile scenario or scenarios to include in the PVA, but we are stuck with no species-specific relationship of predator density to survival, so we will probably follow suite with the Green River; focus on SMB above Westwater and expanding Walleye below.

We include below the scenarios provided by Kevin McAbee:

Scenario 2: Increased carrying capacity via reduced large nonnative fish

Large bodied, nonnative fish species greatly alter the ecosystem of the Colorado River basin upstream of Lake Powell. Populations of northern pike, smallmouth bass, and walleye exist in almost every river mile occupied by Colorado pikeminnow in the Green and Colorado Rivers. Northern pike are at their highest densities in the upper portions of the Yampa and Green rivers, where stream temperatures are colder and shoreline habitats are more vegetated. Pike are found in lower densities in the middle Green River and portions of the upper Colorado River. Smallmouth bass populations overlap with the lower terminus of northern pike presence and continue downstream into warmer habitats, especially occupying nearshore rocky habitats which are abundant in the lower Yampa, middle Green, upper White, and upper Colorado River. Walleye are recent emigrants into the Green and Colorado subbasins, occupying alluvial reaches that are used as nursery habitats by young Colorado pikeminnow, most notably the lower portions of the Green and Colorado rivers, and the middle Green River between Ouray National Wildlife Refuge and Dinosaur National Monument.

Northern pike and smallmouth bass have established large, self-sustaining populations since increases in the early 1990s. Smallmouth bass reproduction is most successful in lower flow, warmer water years.
Longer, warmer growing seasons are provided by lower flows, which permit smallmouth bass to grow to lengths that support over winter survival. Northern pike reproduction is closely linked to access to vegetated backwaters in the Yampa River immediately after ice-off. Walleye populations are hypothesized to be supported primarily from reservoir emigration from locations such as Starvation and Red Fleet Reservoirs (downstream escapement through dams) in the middle Green River and Lake Powell in the lower Colorado and Green rivers (upstream migration into riverine habitats). While larval walleye have been documented, and spawning aggregation discovered, there have not been documented walleye recruitment in riverine habitats.

These three large bodied piscivores have serious and multifaceted impacts on native fish populations through predation and competition. As Breton et al. reported in 2015:

> “The predatory threat of large-bodied piscivorous taxa such as northern pike and smallmouth bass is substantial. For example, based on results of a

bioenergetics model, Johnson et al. (2008) ranked smallmouth bass as the most problematic invasive species because of their high abundance, habitat use that overlaps with most native fishes, and ability to consume a wide variety of life stages of native fishes in the Colorado River Basin. Increasing populations of piscivores such as smallmouth bass are a major impediment to conservation actions aimed at recovery efforts for the four endangered fishes in the Upper Colorado River Basin: Colorado pikeminnow *Ptychocheilus lucius*"

Newly produced age-0 Colorado pikeminnow are at risk from walleye and smallmouth bass predation in alluvial reaches in their first summer of life; this predation includes northern pike once juvenile fish begin immigrating into upstream areas inhabited by northern pike. In fact, predation risk continues for years until they reach sub adult life stages and substantial body sizes. Large northern pike and walleye can consume juvenile and subadult Colorado pikeminnow, as both species have substantial gape size. To reach sexual maturity at ages 7 to 10 years old, and lengths approximating 450 millimeters (mm), young Colorado pikeminnow must avoid predation in diverse habitats, from multiple skilled predators, over a period of many years.

Additionally, because Colorado pikeminnow are the native apex predator of the Colorado River system, they compete directly with large-bodied nonnative piscivores. Limited food resources can impact population dynamics of predator species both via reduced mean body mass (individual condition) or via reduced number of supported organisms (reduced carrying capacity) (McGarvey et al. 2010; Johnston & McGarvey 2011). Data collected for Colorado pikeminnow and nonnative predators demonstrate that adult Colorado pikeminnow appear highly vulnerable to trophic replacement, especially in locations like the Yampa River where densities of adult nonnative predators are substantial (Martinez 2012).
Furthermore, Martinez (2012) concluded that difference between carrying capacity and minimum viable population size was low for Colorado pikeminnow, making it especially at risk for dramatic population declines via resource competition.

Martinez (2012) estimates the historical carrying capacity of Colorado pikeminnow in the Colorado River Recovery Unit as 500 to 800 adult fish (2.1 to 3.3 fish per mile) and adult abundance has been estimated as high as 889 adults (3.7 fish per mile in 2005; Osmundson and White 2014). However, recent adult abundance estimates for Colorado pikeminnow in the Colorado River is substantially less than carrying capacity, with simultaneously elevated catches of nonnative predators (Elverud and Ryden 2016). For example, walleye catches in the lower Colorado River were nominal prior to 2010, but "walleye captures were approximately four times that of adult Colorado pikeminnow in that reach" in 2013 to 2015 (Elverud, pers. comm.).

Management Actions to Reduce Nonnative Fish

In response to the impacts of nonnative predators, Recovery Program stakeholders have implemented nonnative species removal actions. Over the past decade, the Recovery Program has enlarged, researched, and improved the effectiveness and efficiency of its removal program. Since the early 2000s, Upper Colorado Program removal activities have expanded from six miles in the Yampa River to over 600 miles in four rivers. Some river reaches are sampled more than a dozen times annually.

Comprehensive investigations into the effectiveness of the smallmouth bass and northern pike removal programs (Breton et al. 2015 and Zelakso et al. 2014, respectively) have guided efforts to target disruption of reproduction and to limit escapement from upstream reservoirs. As such, the Recovery Program now focuses on removal of large bodied adults, especially in spawning locations, and the prevention of reservoir escapement via screens, nets, and reservoir reclamation projects. It is important to remember that the phase of the nonnative removal program guided by systematic review has only been implemented for about 5 years.

Colorado pikeminnow demographics that currently populate the PVA model represent recent conditions in which nonnative fish flourished. The nonnative removal program was in early development, flows were modified by outdated regimes, and many habitats were not restored. The PVA data assimilation documents indicates that based on body condition and food resources, the apparent carrying capacity of the Colorado River is 1000 adults (4.2 adults per mile; Osmundson, 1999). These numbers slightly exceed those proposed by Martinez et al. (2012) as carrying capacity for the species in the absence of nonnative species.

> Adjusting the carrying capacity of the PVA could model a successful nonnative removal program. Increasing the current carrying capacity from 1000 to 1200, 1400, and 1600 could determine if carrying capacity is an important consideration for species viability.

Limiting the carrying capacity of a species within a modeling exercise would by definition limit the apparent maximum abundance estimate that population can achieve, which indirectly limits the ability of the modeled population to demonstrate rapid abundance increases from high recruitment years (demographic rebound or plasticity) and increases the likely extinction probability by dampened apparent maximums.

Increasing Carrying Capacity of the Colorado Pikeminnow

Niche space opened through the removal of nonnative fish could substantially increase the viability of Colorado pikeminnow through a concurrent increase in carrying capacity. In order to model successful implementation of a nonnative removal program, the carrying capacity of the system could be adjusted upward in increments of approximately 200 to determine if carrying capacity is a limiting demographic rate for Colorado pikeminnow.

Table 3. Suggested incremental increases in carrying capacity to represent large bodied nonnative fish removal.

Recovery Unit	Current modeled carrying capacity	Revised modeled carrying capacities (K) to evaluate reduced competition from large		
Colorado River	1000	1200	1400	1600

Justification

The current nonnative strategy focuses on removing adult life stages of northern pike, walleye, and smallmouth bass in designated critical habitat reaches for Colorado pikeminnow (and certain upstream areas to prevent downstream emigration). Removal efforts have recently focused on targeting species in spawning conditions to enhance the removal of adults. As a result, the size structure of northern pike and smallmouth populations have shifted towards smaller individuals and an overall reduction in catches of large piscivorous individuals[1]. For example, in the middle Yampa River, reduction in the number of northern pike greater than 450 mm since the inception of backwater netting effort in 2014 (see Figure 6 taken from Noble 2016, below) has occurred. Similarly, smallmouth bass greater than 325 mm are rarely captured during typical removal efforts, with catches typically dominated by sizes less than 250 mm (Figure 7 taken from various reports, below).

While this may not necessarily mean a reduction in the capability of these species to persist as self- sustaining populations, it does reduce the effects of competition at the highest trophic levels. As a result, this should result in steadily increasing carrying capacity for adult Colorado pikeminnow.

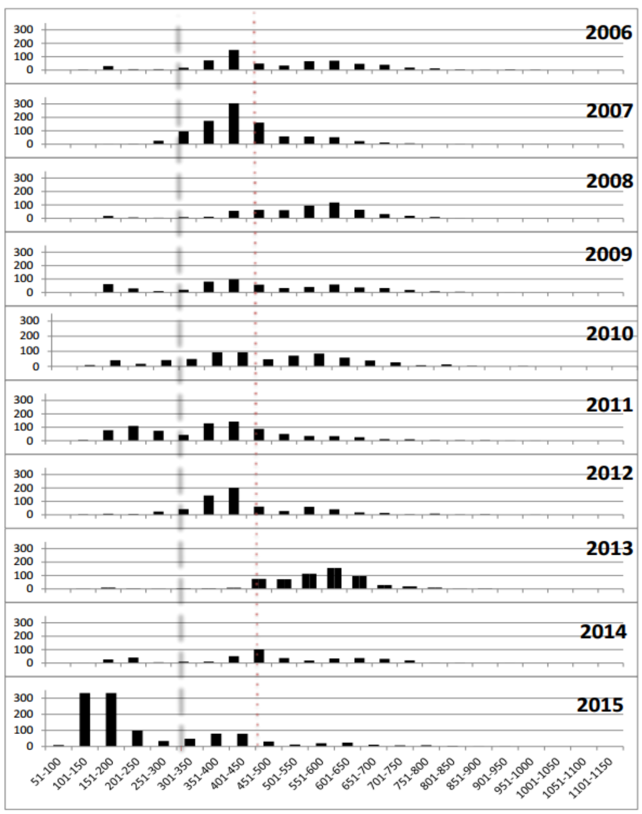

Figure 6. Northern pike size structure in the middle Yampa River as presented by Noble (2015). Dotted vertical line represents 450 mm, indicating a direct competitor to adult Colorado pikeminnow. Dashed vertical line indicates 300mm, or the demarcation of adult northern pike. Note the shift in size structure from adult fish in 2009 to 2012 to very large adults in 2013 and the dramatic reduction in adult and large adults in 2014.

[1] Martinez (2012) estimated that a 450 mm northern pike, a 325 mm smallmouth bass, and a 375 mm walleye is the biomass equivalent of an adult Colorado pikeminnow (450 mm).

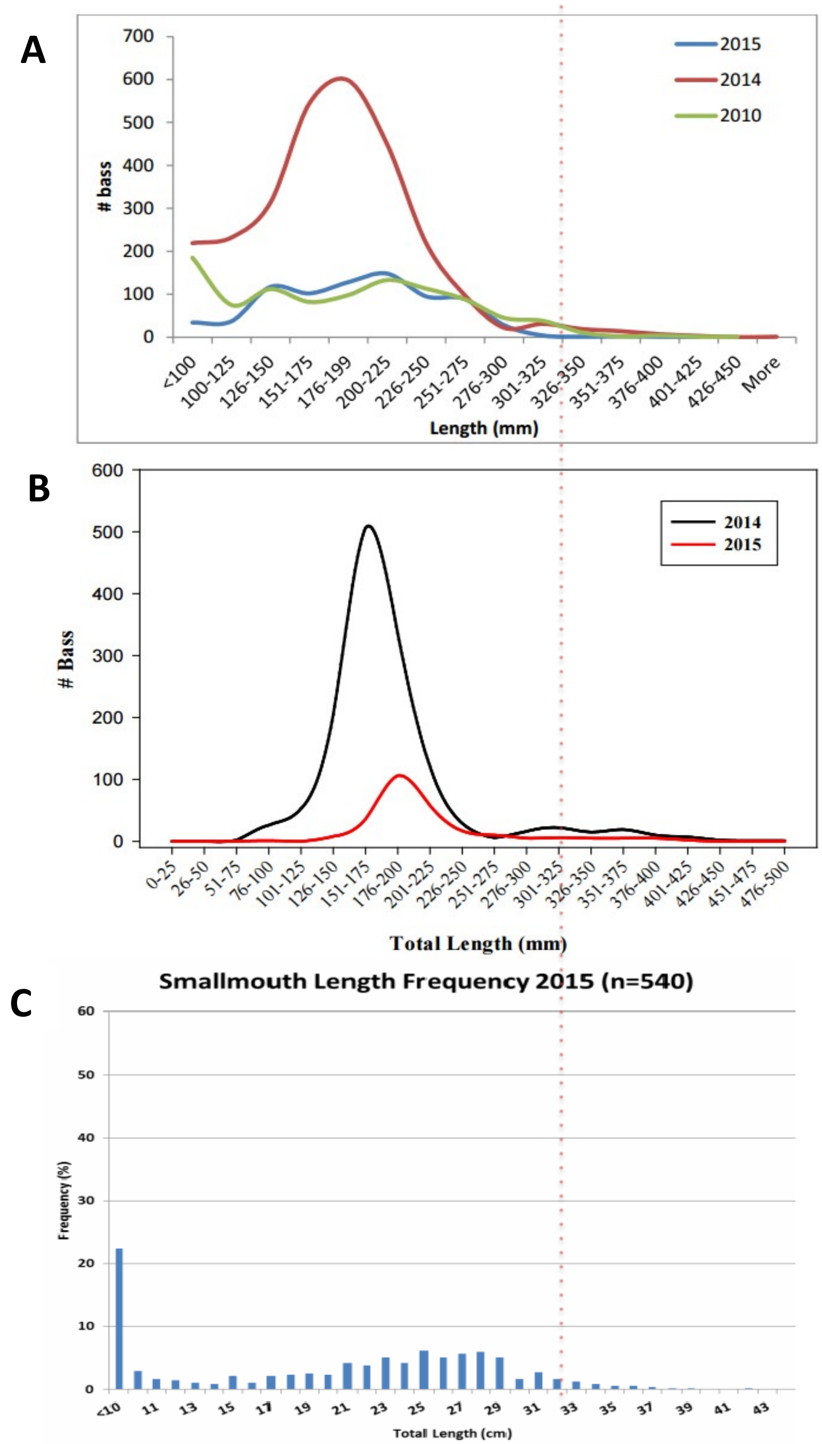

Figure 7. Size structure of smallmouth bass captured in portions of designated critical habitat for Colorado pikeminnow in the Green and Colorado Rivers. A: Echo Park to Split Mountain in 2010, 2014, and 2015 (Jones et al. 2015); B: Desolation and Gray Canyons 2014 and 2015 (Jones et al. 2015); C: Colorado River from Silt, CO to the Green River confluence (Francis and Ryden 2016). Dotted vertical line represents 325 mm, indicating a direct competitor to adult Colorado pikeminnow according to Martinez (2012). Note C has a differing Y axis (percent) than A&B (total abundance). In box A, similar size structure of 2010 and 2015 result from both years being 3 years after a low flow, high smallmouth bass production year.

Scenario 3: Increased survival of young Colorado pikeminnow via reduced nonnative fish predation

The reduced numbers of large nonnative piscivorous fish is appropriate to consider for adjustments to carrying capacity within the model (Scenario 2 above). However, the abundant numbers of walleye and smallmouth bass below those size limits (Figure 7 above) still represent a large predatory threat to young pikeminnow, especially age-0 and age-1 individuals in nursery habitats. Smallmouth bass are able to prey upon young Colorado pikeminnow in their first summer of life, representing a pronounced predatory threat, especially in lower flow years. Researchers have also documented walleye predation on Colorado pikeminnow as large as 300 mm (Francis and Ryden 2014), indicating that the predatory threat from nonnative species occurs in multiple years of early development (Bestgen and Hill in draft 2016).

The importance of age-0 production of Colorado pikeminnow for the maintenance of subsequent adult populations was demonstrated previously in scenario 1. In order to truly realize gains in Colorado pikeminnow production within nursery habitats from altered flow regimes, managers must counter the considerable negative impact that large numbers of smallmouth bass and walleye have on age-0 and age-1 pikeminnow in those habitats. As mentioned in scenario 2, the implementation of nonnative fish control actions has only recently reached a condition that the Recovery Program believes is sufficient to alter nonnative fish population dynamics.

Conditions considered in the PVA represent a period of reference where annual hydrology was frequently dry (see scenario 1), which allowed smallmouth bass to flourish in many Colorado River habitats. For example, the annual hydrology of 2007, 2010, 2012, and 2013 were quite conducive to high smallmouth bass production. Conditions considered in the PVA also represent the colonization of walleye in nursery habitats, prior to specific walleye removal efforts (Bestgen and Hill 2016 in draft).

To truly model the future conditions for Colorado pikeminnow, a new set of parameters should be considered that represent the commitment by Recovery Program stakeholders to continue to implement the nonnative management actions that are known to be the most effective and efficient.

Nonnative removal efforts:

The current strategy for removal of smallmouth bass is guided by a decade of field work, population dynamics modeling, and resulting suppression strategies. In addition, the Recovery Program also specifically targets walleye for removal, which is an additional action. As a result, the Recovery Program believes that in the future, its management of smallmouth bass and walleye will be more effective than the last decade. Key components of this strategy include:

- The removal of smallmouth during the spawning period is a core component of the nonnative fish management strategy and includes enhanced effort in multiple locations during this critical time.
- Harvest regulations now either allow anglers to catch unlimited amounts of smallmouth bass in the basin (Colorado), or expressly prohibit the return of this species to upper basin waters inhabited by endangered fish (Utah and Wyoming).

- Removal of walleye is now a consistent part of mechanical removal efforts. Walleye have not demonstrated recruitment in rivers yet.

Therefore, under future conditions, population control for walleye and smallmouth bass can be assumed to be more effective than what was implemented in the mid-2000s. Concurrently, survival of age-0 Colorado pikeminnow will be elevated as a result of increased control. In fact, this may be one reason that age-0 Colorado pikeminnow catches are quite high in 2015 and 2016. That is, these recent years are providing both flow and fish community conditions that provide niche space for adequate age-0 Colorado pikeminnow production.

PVA scenario

In order to model improved nonnative species management, increases in the survival rates of Colorado pikeminnow from age-0 to sub-adult stages (~300 mm) by a factors of 5% up to 20% are justified. For example, PVA input parameters quantify survival of age-0 cohorts are 20.7% in the Green River Recovery Unit (Bestgen unpublished data). Modeling survival rates of 21.7%, 22.8%, 23.8%, and 24.8% could demonstrate management actions have a meaningful impact to Colorado pikeminnow. Modeling this increase for all cohorts simultaneously is most logical; that is, in a revised model, increases to all cohort survival rates should be equivalent for ages 1 to 5.

In order to model improved nonnative species management, an increase in the survival rates of Colorado pikeminnow from age-0 to sub-adult stages (~300 mm) by a factors of 5% up to 20% could be used.

Moderate increases in survival, such as 5 and 10% are plausible under more effective mechanical removal that is currently being implemented. More aggressive increases in survival, such as 15 and 20%, are a potential outcome of basin-wide reductions in smallmouth bass, such as implementing a smallmouth bass spike flow (Bestgen and Hill 2016).

Table 4. Suggested incremental increases in survival rates to represent nonnative fish removal.

	Age-1	Age-2	Age-3	Age-4	Age-5
Existing survival rate in PVA model	0.207	0.309	0.411	0.514	0.616
5% increase	0.217	0.325	0.432	0.539	0.646
10% increase	0.228	0.340	0.452	0.565	0.677
15% increase	0.238	0.356	0.473	0.591	0.708
20% increase	0.248	0.371	0.494	0.616	0.739

3. Range Expansion through Fish Passage

Establishing pikeminnow populations in the Gunnison River upstream of Redlands Dam, the Colorado River upstream of Government Highline Dam and potentially the Dolores River would increase the carrying capacity of pikeminnow within the Colorado River. Each of these three river sections would likely require a separate management action to establish pikeminnow. The Dolores would likely benefit from increase flows. The Gunnison may benefit from increasing temperature by installing a temperature control devise on the Aspinall unit. Establishing pikeminnow above Government Highline may require translocating adult pikeminnow or stocking juveniles. All three of these management actions would present significant obstacles.

Upper Colorado River

Fish passage structures have been installed on the Grand Valley Irrigation Company low-head diversion (RM 185, nonselective, 1998), Grand Valley Project Dam (RM 194, selective, 2004), and Price-Stubb roller dam (RM 188, nonselective, 2008). Small numbers of Colorado pikeminnow have been handled at these facilities indicating that upstream population expansion could occur if enough fish moved, and if food supply and temperature regimes were suitable. The Grand Valley Project and Price-Stubb fish passages allow access to critical habitat that extends upstream to Rifle, Colorado (RM 240); through 2013, 13 Colorado Pikeminnow have been detected using the Price-Stubb fish passage.

To approximate the number of adult Colorado pikeminnow that could occupy new habitat upstream of fish passage structures, we used the fish densities provided by Osmundson and White (2014). They divided the Upper Colorado River into two reaches: (1) lower reach from the Green River confluence (RM 0) upstream to the lower end of Westwater Canyon (RM 112), and (2) upper reach from the upper end of Westwater Canyon (RM 124) upstream to the fish passage structures at RM 188 (1991-2005; Grand Valley Project) and RM 193.7 (2008-2010; Price-Stubb).

Based on abundance point estimates, Osmundson and White (2014) estimated densities of Colorado pikeminnow > 450 mm TL (i.e., adults) in the lower reach ranged from 1.4 to 4.4 fish/mile (0.85 to 2.7 fish/km) with a mean of 2.7 fish/mile (1.6 fish/km). Upper-reach density in 2005, the year with the highest abundance, was 7.5 fish/mile (4.7 fish/km), assuming 477 adults over 63.5 miles. This established the actual numbers of adults in each of the two reaches, but Osmundson and White (2014) believed that the population was likely limited by the infrequency of strong year classes rather than food resource limitations, and an expansion of adult density was computed, based on food resources.

Osmundson et al. (2002) documented electrofishing catch rates of forage-size fish (100–300 mm TL) 4.5 times higher in the upper reach than in the lower reach during a 1994–1995 study. They therefore surmised that the upper reach was capable of supporting higher densities of adult-size Colorado pikeminnow than the lower reach. Once in the upper reach, body condition improved with increased length, suggesting improved feeding opportunities for adults and a surplus of forage. Using the mean density of 2.7 fish/mile as what the lower reach might generally support, along with the above comparison of forage abundance in the two reaches, they derived an estimate of 11.6 adults/mile (7.2 adults/km) as the potential density for the upper reach.

This gives us an approximation of the density of adults that might be possible upstream of the fish passage structures on the Upper Colorado River. However, there is an upstream limitation of potential habitable area by Colorado pikeminnow based on water temperature. At some distance upstream, annual thermal units decline to the point where plentiful forage can no longer provide adequate compensation and temperature becomes too low for growth. Kaeding and Osmundson (1989) determined that Colorado Pikeminnow need habitat with 40 annual thermal units (ATU). Osmundson et al. (1998) believed that the upstream limit for Colorado pikeminnow is probably within the reach immediately upstream of the Grand Valley where annual thermal units are low. At Rulison, mean daily temperatures never reached 20□C during 3 of the 5 years studied. Black and Bulkley (1985a, 1985b) found that growth of yearling Colorado squawfish held at 20□C and fed unlimited food was only 54% that of growth at the optimum temperature of 25□C.

If we assume that Rulison (RM 232) is the upstream boundary for Colorado pikeminnow thermal requirement, upstream-most fish passage at the Grand Valley Project (RM 194), we surmise that 38 miles of habitat are available in the Upper Colorado River. If we assume that forage upstream of RM 194 is similar to the upper reach, and at a potential density of 11.6 adults/mile, we conclude a total potential of 441 adults for the 38 miles of new habitat. If we assume an actual density of 7.5 adults/mile in the upper reach, we conclude a total of 285 adults in the new habitat. **These estimates of 441 adults and 285 adults provide respective approximations of potential and actual numbers of adults possible in the Upper Colorado River as a result of fish passage.**

Gunnison River

A selective fish passage structure was installed on the Redlands Water and Power Company diversion at RM 2.2 of the Gunnison River in 1996. The Redlands fish passage allows upstream access to an estimated 37 miles of thermally suitable, historical habitat (Osmundson 2011); through 2013, 124 Colorado Pikeminnow used this passage. Critical habitat extends 68 miles up the Gunnison River.

The Gunnison River is smaller than the Upper Colorado River, and we assume a lower capacity of fish per mile. **If we assume that the density of 7.5 adults/mile, from the upper reach of the Colorado River, is a reasonable potential density for the Gunnison River, we surmise that the 37 miles of habitat upstream of fish passage could support 278 adults.** This assumes that the thermal regime could be modified with penstock modification at the Aspinall Unit dams (i.e., Blue Mesa). Studies for a multiple-level selective withdrawal structure at Blue Mesa Dam show that temperature modification is possible for the Gunnison River (Hydrosphere Resource Consultants 2002; Boyer and Cutler 2004).

4. Augmentation from Hatchery Stocking

Augmentation of the Colorado Pikeminnow population during extended periods of negligible recruitment. Between 2005-2012, few juveniles (250-450 mm TL) pikeminnow were present with the Colorado River (Range = 49-158 individuals). During this period, the adult population of pikeminnow decreased from ~900 fish in 2005 to ~332 fish in 2013 due to recruitment not keeping up with mortality. We realize this management option may not be popular, but is likely more feasible than many other scenarios.

There have only been two stocking events of Colorado Pikeminnow in the Upper Colorado River. About 1,500 juveniles were Carlin-tagged and transferred from the Willow Beach National Fish Hatchery, AZ, for release in the Colorado River near Moab, UT (RM 47.3) in April 1980 (Valdez et al. 1982). Thirteen of these fish were recaptured 1-14 months after release at distances of 0.9-45.8 miles from the release site.

A second stocking was a total of 2,248 hatchery-reared Colorado Pikeminnow transferred from the Dexter National Fish Hatchery and released in the Gunnison River during 2003 and 2004. None of these stocked fish were recaptured in the Gunnison River (Osmundson and White 2009), which suggests that the retention of Colorado Pikeminnow in the Gunnison River is low (Burdick 2001). Compared to the mainstem, the Gunnison River upstream of the Redlands Water and Power Company Diversion has considerably fewer nonnative fish and a similar or higher abundance of appropriate-sized forage fish to serve as available prey for subadult and adult Colorado Pikeminnow (Burdick 1995; Osmundson 1999).

For this scenario, we suggest modeling stockings and survival rates similar to those observed in the San Juan River.

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Appendix A: Data used to construct PVA input table for the Colorado River Recovery Unit

Year	Stateline Flow	CPE per 100m^2	CPE per 10m^2	Total Produced 1986-2014	Total Produced McAda Flow Recs	Total Produced Revised Flow Recs
1986	6106.5	14.29	1.429	102219.1	~~102219.1~~	102219.1
1987	4058.5	7.91	0.791	56581.74	56581.74	56581.74
1988	3319.5	4.54	0.454	32475.49	32475.49	32475.49
1989	3071.5	3.53	0.353	25250.76	25250.76	25250.76
1990	2667	6.98	0.698	49929.27	49929.27	49929.27
1991	3985.5	6.61	0.661	47282.59	47282.59	47282.59
1992	3537	4.12	0.412	29471.15	29471.15	29471.15
1993	4850.5	7.21	0.721	51574.51	51574.51	51574.51
1994	3051.5	4.52	0.452	32332.42	32332.42	32332.42
1995	6545.5	2.94	0.294	21030.38	~~21030.38~~	~~21030.38~~
1996	3800	21.05	2.105	150574.7	150574.7	150574.7
1997	7332	0.43	0.043	3075.872	3075.872	3075.872
1998	4289	1.89	0.189	13519.53	13519.53	13519.53
1999	6432.5	0.28	0.028	2002.893	~~2002.893~~	~~2002.893~~
2000	3504	6.23	0.623	44564.38	44564.38	44564.38
2001	3513	0.42	0.042	3004.34	3004.34	3004.34
2002	1845.5	0.82	0.082	5865.617	5865.617	~~5865.617~~
2003	3148.5	0	0	0	0	0
2004	2945.5	0.99	0.099	7081.659	7081.659	7081.659
2005	4114.5	1.1	0.11	7868.51	7868.51	7868.51
2006	4388.5	0.24	0.024	1716.766	1716.766	1716.766
2007	4075	0.86	0.086	6151.744	6151.744	6151.744
2008	4898.5	0	0	0	0	0
2009	3869.5	9.46	0.946	67669.19	67669.19	67669.19
2010	3835	1.03	0.103	7367.787	7367.787	7367.787
2011	5540	4.94	0.494	35336.76	35336.76	35336.76
2012	2605	2.41	0.241	17239.19	17239.19	17239.19
2013	3715	0.05	0.005	357.6595	357.6595	357.6595
2014	4912.5	0.31	0.031	2217.489	2217.489	2217.489
2015	3994.5	106.39	10.639	~~761028~~	~~761028~~	~~761028~~
			mean	28406	26866	30572
			std dev	33694	32023	34830

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

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In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

7. McAbee, K. 2017c. Colorado River summer base flow scenario for PVA consideration. Report prepared for the Colorado Pikeminnow PVA Technical Team.

Colorado River summer base flow scenario for PVA consideration

The concepts supporting the revised flow recommendations for Colorado pikeminnow age-0 production in the Green River are also applicable in the Colorado River. Using the same general process as Bestgen and Hill (2016), and using long term monitoring of age-0 Colorado pikeminnow production in the Colorado River (1979-2016), we can analyze age-0 production as a function of flow at the Colorado River near the Colorado / Utah State Line (gage #09163500).

Long term annual monitoring of age-0 Colorado pikeminnow in the Colorado River began in 1979 and continues today (Figure 1).

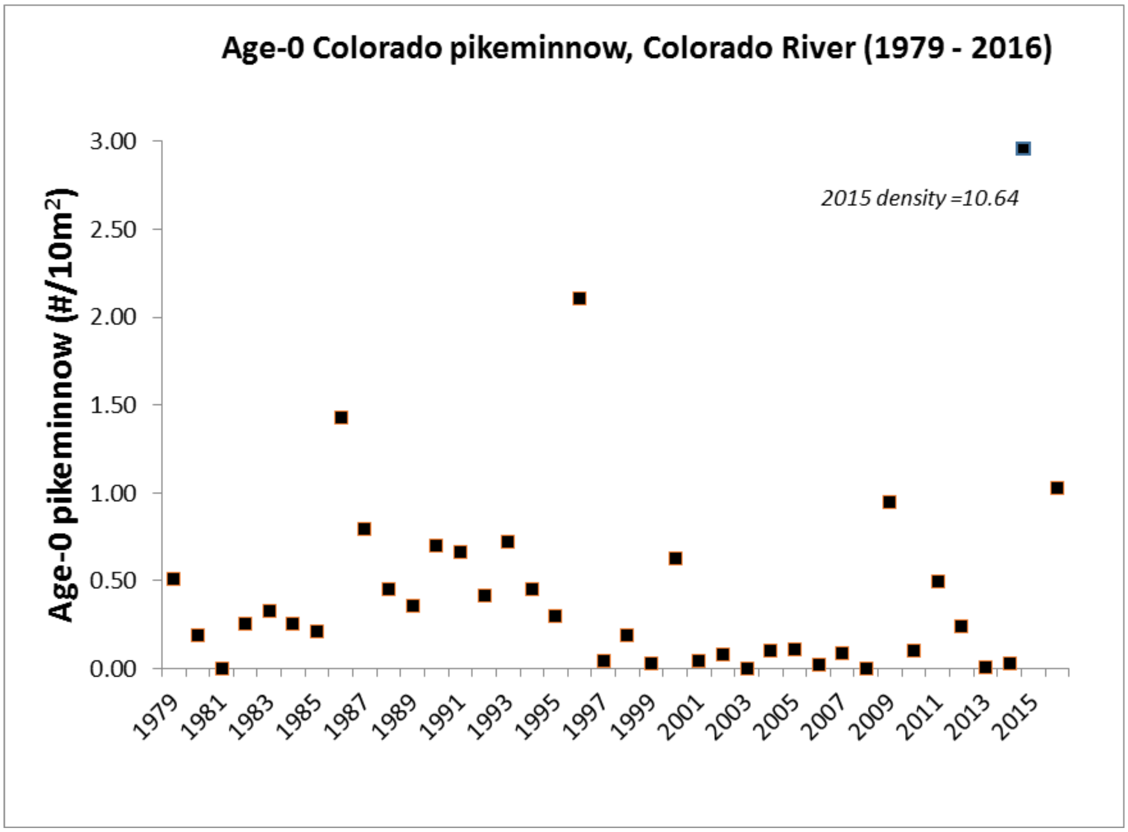

Figure 1. Annual age-0 Colorado pikeminnow density in the Colorado River since 1986. The mean for the entire period of record is 0.66 Colorado pikeminnow / $10m^2$

Mean August and September base flows in the lower Colorado River (Figure 2) have declined through the period of record, which was influenced by extremely high flows of 1983 and 1984 which occurred early in the period. This general trend in summer base flows is similar to the declines reported on the Green River. The range of annual summer base flow also appears to have decreased since 2000.

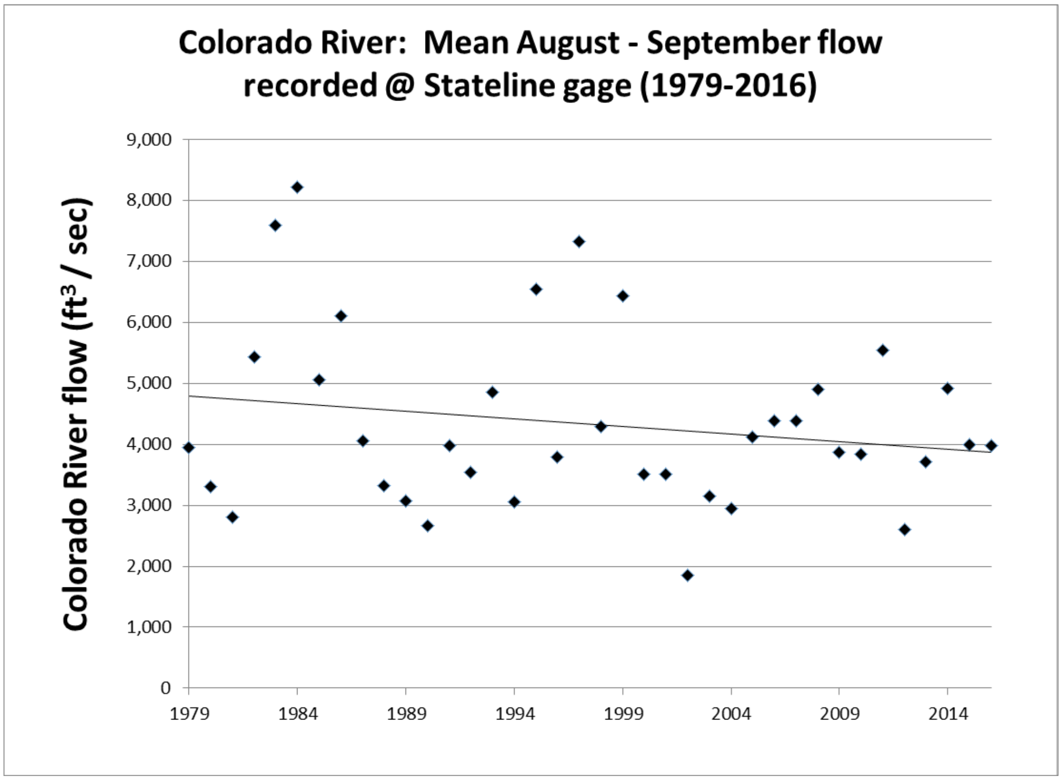

Figure 2. Mean August thru September base flow measured at the Colorado / Utah State Line gage.

Analyzing age-0 pikeminnow production as a function of mean August to September flows (Figure 3) demonstrates a similar, albeit more variable, pattern as that shown in Bestgen and Hill's (2016) Figure 18. That is, moderate flows show an increase in age-0 production, with extremely higher and lower flows demonstrating lower production.

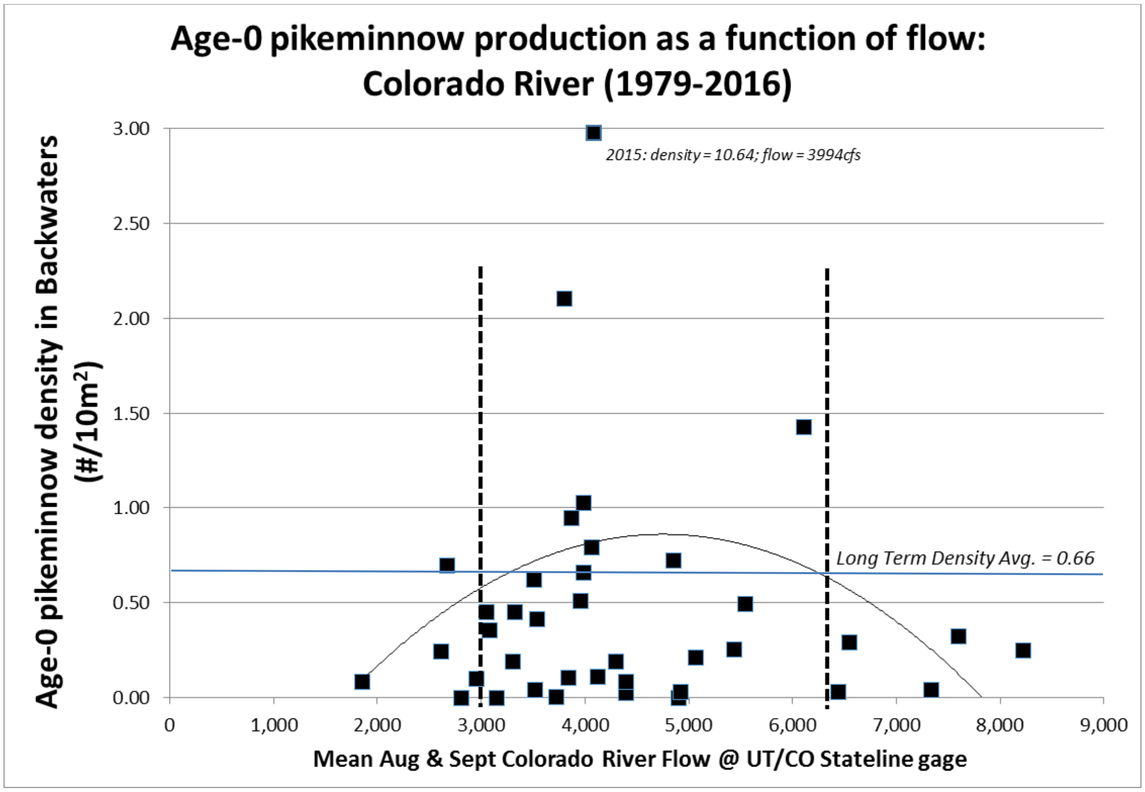

Figure 3. Age-0 Colorado pikeminnow density as a function of mean August and September flow. Note the parabolic relationship similar to that presented in Bestgen and Hill's (2016) Figure 18 is present. Vertical dashed lines bound a preferred base flow range. Long term average density ($0.66/10m^2$) is represented by the blue cross bar line. The 2015 data point (density = 10.64; flow = 3,994 cfs) was included in this analysis.

Table 1. Flow recommendations and ecological goals of the Colorado River as measured at the Colorado / Utah state line gage as described in McAda 2003.

	Exceedance	Lower base flow recommendation	Upper base flow recommendation	Ecological goal
Dry	90-100%	1800	2500	Backwater habitats are available, but not maximized; high Colorado pikeminnow growth rate
Moderately Dry & Below Average	50-90%	2500	4000	Backwater quantity and area are maximized; constant habitat and warm water allow for elevated growth and production of Colorado pikeminnow
Above Average & Moderately Wet	10-50%	3000	4800	
Wet	10%	3000	6000	Backwaters available but fewer and smaller

Current flow recommendations for the Colorado River (Table 1) call for summer base flows in the range of 1800-6000 cfs, based on annual hydrologic conditions. This range incorporates the bulk of the flow conditions since 1979 (see Fig. 2). The goals of these recommendations are to provide backwaters in all years, and to maximize the availability in moderate years. By analyzing the mean age-0 Colorado pikeminnow production across these flow recommendations, we can indirectly determine their ability to meet the ecological goals of each category (Table 2).

Since 1979, flows have occurred in the dry year classification (1800 to 2500) and the lower portion of the moderately dry classification (2500 to 3000 cfs) five times. Annual age-0 production was below the long term average (0.66 age-0 pikeminnow / 10m^2) in four of those years. Similarly, only one in six of the wettest hydrologies (Aug-Sept flows > 6,000 cfs) exceeded the long term average.

Table 2. Mean age-0 production of Colorado pikeminnow under McAda (2003) flow recommendations. The parenthetical represents the number of years that fall into that category, due to the overlap among the recommendations and categories, rather than 38 years in the data, there were 69 years falling within these categories.

	Lower base flow recommendation	**Upper base flow recommendation**	**mean age-0 CPM produced per 10m^2**
Dry (n=1)	1800	2500	0.08
Moderately Dry & Below Average (n=20)	2500	4000	0.98
Above Average & Moderately Wet (n=21)	3000	4800	0.94
Wet (n=27)	3000	6000	0.88

If we follow the pattern that Bestgen and Hill (2016) undertook when revising the Muth et al. (2000) flow recommendations, we can approximate similar revised flow recommendations for the Colorado River. Bestgen and Hill (2016) increased the minimum flow recommendation in dry years to a flow level that yielded meaningful production (from 900 cfs to 1700 cfs in the middle Green River and from 1300 to 1700 in the lower Green River). In the Colorado River, if dry year minimum flow recommendations were increased from 1800 to 3000 cfs, mean production would increase substantially for that hydrologic year type (Table 3; Figure 3). Bestgen and Hill (2016) also recommended selecting a wet year maximum flow level that precluded low Colorado pikeminnow production by limiting overtopping of backwaters and cold water growing conditions. In the Colorado River, if we simply increased McAda's (2003) wet year maximum by 400 cfs, we include an additional high production year.

To quantify that potential increase, we can compare the mean annual production under each hydrologic classification using the current and revised flow recommendations (Table 3). By increasing the dry year classification up to 3000 cfs, we eliminate some of the poorest production years on record. Increasing the dry year minimum to 3000 increases age-0 density by 300%, which seemingly meets the ecological goal found in McAda 2003.

Table 3. Comparison of age-0 production under current and revised flow regimes.

Hydrologic classification	McAda et al. recommendations		mean CPM produced per 10m^2	Revised flow recommendations to increase age-0 production		mean CPM produced per 10m^2	Increase in production (% increase)
Dry	1800	2500	0.08	3000	3600	0.32	0.24 (300%)
Moderately Dry & Below Average	2500	4000	0.98	3600	4700	1.32	0.34 (34%)
Above Average & Moderately Wet	3000	4800	0.94	3900	5500	1.09	0.15 (16%)
Wet	3000	6000	0.88	3900	6400	1.07	0.19 (22%)

By shifting the lower minimum flow recommendation up and commensurately raising other hydrologic year flow recommendations, we can increase the age-0 Colorado pikeminnow production in each year category (Table 3). While these flow recommendations are purely hypothetical (having not received peer review) and would potentially be difficult to implement (they would have to be vetted substantially), they offer a test case for PVA implementation.

Age-0 production in 2015 was exceptionally high; approximately four times higher than the next highest density and 15 times greater than the long term average. In 2015, mean flows at the Colorado / Utah Stateline gage were 3994 cfs which fall within the average classifications in both the current and revised recommendations. Even more interesting is the fact that both of the two highest production years were very close in flow magnitude – 3994 cfs in 2015 and 3800 cfs in 1996.

Input to the PVA Colorado River Flow Scenario:

Estimates of annual age-0 production were calculated from annual density estimates as described in the Green River flow scenario. To provide a revised input table for PVA management scenario modelling, we describe age-0 production in two categories: a) when August through September base flows fall within the preferred based flow range (3000 – 6400 cfs) and b) when base flows were outside this range (<3000 cfs; >6400 cfs) (Table 4).

Table 4. Revised input parameters for PVA analysis.

	Density of age-0 in years 1979 to 2016 (all years)	Density of age-0 in years (n=10) not meeting the preferred base flow recommendations (<3000 cfs; > 6400 cfs)	Density of age-0 in years (n=28) meeting preferred base flow recommendation (>3000 & <6400 cfs);
Mean	46,923	14,750	58,413
Standard deviation	121,427	14,216	139,415

From 1979 through 2016, observed August through September base flows fell within the preferred range 28 times, i.e., approximately 75% of the time. Therefore we suggest applying the preferred / non-preferred production rates to baseline and management scenarios as follows:

1. Baseline – preferred production in 75% of years; the lower production values associated with non-preferred base flow conditions in 25% of years.

2. Management #1 – preferred production rates in 90% of years; lower production in 10%

3. Management Ideal – preferred production in 100%

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Appendix: Data used to construct Colorado River Flow Management Scenario for a Population Viability Analysis

Year	**Mean Aug – Sept flow recorded at the USGS gage near the CO/UT State Line**	**Age-0 pikeminnow density (# / m^2)**	**And estimate of the Total # of age-0 pikeminnow produced**
1979	3,951	0.51	36481.27
1980	3,304	0.19	13591.06
1981	2,800	0.00	0.00
1982	5,430	0.25	18169.11
1983	7,591	0.33	23319.40
1984	8,221	0.25	17954.51
1985	5,066	0.21	15021.70
1986	6,107	1.43	102219.10
1987	4,059	0.79	56581.74
1988	3,320	0.45	32475.49
1989	3,072	0.35	25250.76
1990	2,667	0.70	49929.27
1991	3,986	0.66	47282.59
1992	3,537	0.41	29471.15
1993	4,851	0.72	51574.51
1994	3,052	0.45	32332.42
1995	6,546	0.29	21030.38
1996	3,800	2.11	150574.67
1997	7,332	0.04	3075.87
1998	4,289	0.19	13519.53
1999	6,433	0.03	2002.89
2000	3,504	0.62	44564.38
2001	3,513	0.04	3004.34
2002	1,846	0.08	5865.62
2003	3,149	0.00	0.00
2004	2,946	0.10	7081.66
2005	4,115	0.11	7868.51
2006	4,389	0.02	1716.77
2007	4,389	0.09	6151.74
2008	4,899	0.00	0.00
2009	3,870	0.95	67669.19
2010	3,835	0.10	7367.79
2011	5,540	0.49	35336.76
2012	2,605	0.24	17239.19
2013	3,715	0.01	357.66
2014	4,913	0.03	2217.49
2015	3,995	10.64	761099.52
2016	3,986	1.03	73677.87

Population Viability Analysis for the Colorado Pikeminnow (*Ptychocheilus lucius*)

An Assessment of Current Threats to Species Recovery and Evaluation of Management Alternatives

Report prepared by

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In consultation with

The Colorado Pikeminnow PVA Technical Team

SUPPORTING INFORMATION

8. Durst, S.R. 2017. San Juan River Basin scenarios for Colorado Pikeminnow PVA. Report prepared for the Colorado Pikeminnow PVA Technical Team.

San Juan River Basin scenarios for Colorado Pikeminnow PVA

Scenarios simulating conservation actions that affect demographic parameters like survival and fecundity for Colorado Pikeminnow in the San Juan River are hampered by a lack of data to quantify the functional relationship between management actions and variables used in the PVA model. Nevertheless, scenarios in Kevin McAbee's document "Incorporating Recovery Program Conservation Actions into the PVA Modeling Framework: Multiple Test Cases" and Phil Miller's "A Population Viability Analysis for the Colorado Pikeminnow in the San Juan River" provide a foundation for further exploration of this topic in the San Juan River.

This document summarizes a variety of potential management actions that could be implemented in the San Juan River and their hypothesized impact on Colorado Pikeminnow PVA demographic parameters. The likelihood of implementing any of the new management scenarios is unknown. Additionally, there are likely varying levels of support within the San Juan River Basin Recovery Implementation Program to implement or continue these management actions.

Increased survival of young Colorado Pikeminnow via reduced nonnative fish predation (similar to McAbee's scenario 3)

Lacking San Juan River specific data on the relationship between nonnative fish predation and young Colorado Pikeminnow survival, the suggestions developed by McAbee could be similarly applied to the San Juan River Colorado Pikeminnow PVA to simulate the survival benefit for ages 1-5 based on reduced nonnative predation. See Table 4 on page 12 of McAbbe's document.

Increased stocking of Colorado Pikeminnow in the San Juan River

Currently 400,000 age-0 Colorado Pikeminnow are stocked into the San Juan River annually in November. In the San Juan PVA this results in 6,000 ± 1,000 age-1 fish "effectively" added to the population annually. If we assume similar age-0 to age-1 survival of stocked Colorado Pikeminnow, the "effective" stocking rate can be increased by increasing the number of age-0 fish stocked each November. Absent density dependent effects, stocking 800,000 age-0 Colorado Pikeminnow would result in "effectively" augmenting the age-1 population by 12,000 fish each year. Alternatively, improving the effectiveness of the Program's age-0 stocking efforts may increase age-0 to age-1 survival of stocked Colorado Pikeminnow. In theory, this would result in more age-1 Colorado Pikeminnow, while keeping the number of age-0 fish stocked constant.

Increasing San Juan PVA carrying capacity via reestablishing Colorado Pikeminnow populations in the upper San Juan River and Animas River

If upstream reaches of the San Juan River below Navajo Dam can be thermally modified to have the same adult Colorado Pikeminnow carrying capacity as Reach 6 (i.e., 5 fish/mile; per P. Miller Table 3 page 13 based on B. Miller (2013)), those 44 river miles would support an additional 220 adult Colorado Pikeminnow in the San Juan River. Furthermore, if passage barriers and entrainment risks are minimized, assuming the Animas River upstream to Durango, Colorado has a similar carrying capacity to Reach 6 on the San Juan River, those 56 river miles would support an additional 280 adult Colorado Pikeminnow. The increased carrying capacity of these currently unoccupied reaches would more than double the current carrying capacity in the San Juan PVA. Perhaps the carrying capacity in the model could be incrementally increased from 400 adults (baseline the current model) to 900 simulating the hypothetical effect of management increasing the population's carry capacity.

Update San Juan River-specific Colorado Pikeminnow age-specific survival estimates

Although not a scenario for the PVA model, efforts are underway to develop San Juan River-specific, age-specific survival estimates for Colorado Pikeminnow. When these estimates are available, they can be included to update the model to more accurately reflect the Colorado Pikeminnow population in the San Juan River.